TECHNOLOGY EXCHANGE AND TRAINING OF ACTIVE, RECOVERY HYDROPONIC SYSTEMS FOR VEGETABLE PRODUCTION IN THE GAUTENG PROVINCE, SOUTH AFRICA

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EXECUTIVE SUMMARY

This report is based on the WRC K4: Water Utilisation in Agriculture, Project No. (C2019/2020-00229), titled: Technology exchange and training of active, recovery hydroponic systems for vegetable production in the Gauteng Province, South Africa. The project was implemented by the Agricultural Research Council – Vegetable, Industrial and Medicinal Plants (ARC-VIMP) in collaboration with Agang Bokamoso Farms (pty) Ltd (AB Farms – a 100% black-youth owned company, duly registered in accordance with the laws applicable in the Republic of South Africa, with registration number: 2017/024902/07). The research was conducted for four consecutive years, from April 2020 to March 2024, in the Gauteng Province of South Africa. The investigation was set out to explore the potential of hydroponics and provide training and exchange of practical technology of active, recovery (recirculating) hydroponic systems for vegetable production within the smallholder farming sector. This would potentially contribute to economic and social transformation of smallholder farmers through acquisition of better farming knowledge and improved agricultural productivity. The project rationale was based on the fact that hydroponics crop production requires skilled personnel for its implementation and, therefore, for sustainable development of the industry, knowledge and practical experience on hydroponic technologies operation, management and maintanance are required. This would contribute to a more efficient utilization of water resources, which is particularly important in South Africa, as a water scarce country. The following objectives were formulated in order to achieve the project aim: (1) To understand the state of hydroponics and urban farming in Gauteng and its potential to form part of mainstream commercial agriculture (in terms of total available market and serviceable market) and to solve environmental problems; (2) To understand the needs and goals of selected smallholder farmers in the field of crop production, as well as their past experiences with the implementation of conventional soil versus hydroponic production systems; (3) To test the operation, determine optimal operating parameters and conduct cost-benefit analysis of selected recirculating hydroponic systems; (4) To evaluate optimum performance practices at farmers sites, with farmers participatory intervention, and (5) To develop educational materials on the use of recirculating hydroponic systems.

In order to achieve the scope of the project, the research team began by conducting a comprehensive literature review on past knowledge of recirculating hydroponic systems, including an assessment of the state of Gauteng Province population dynamics, food security, water and energy resources for food production. The information is reported in chapters 2 and 3 of this report. The next step taken to meet the project aim was to test various crop management practices, including planting spacing and densities, growing media types, water

flow rates, followed by determination of water and nutritional water productivity under the cultural practives investigated on selected high-value vegetable and herb crops grown in recirculating hydroponic systems in different non-temperature controlled hydroponic structures. The performance of the most productive crop management practices was validated under on-farm conditions. Cost-benefit analyses were conducted on selected hydroponic crop management practices investigated and postharvest technologies developed and tested to improve farmers market access and profitability.

Findings obtained through the implementation of this project revealed that recirculating hydroponic systems are gaining increasing popularity, not only in South Africa but also worldwide. The most commonly implemented systems are the horizontal nutrient film technique (NFT), the ebb-and-flow and the gravel film technique (GFT). These systems often operate under shade nets, which is the most popular type of structure used for hydroponics production particularly in South Africa, followed by non-temperature controlled tunnels. The NFT system operating under shade nets is generally used for growing leafy vegetables, with lettuce being the most dominant crop, while the same system operating in non-temperature controlled tunnels and greenhouses is often used for growing fruity crops, with strawberry being the most dominant one. The ebb-and-flow technique is mainly practiced to grow commercial fruity vegetables like tomato, cucumber and pepper. The GFT system on the other hand, is well suitable for growing both, leafy and fruity vegetables. Research on vertical NFT systems under both, controlled and non-controlled environmental conditions is still very limited, despite the noticeable potential of these systems for increased land, water and nutrient use efficiencies in crop production. The literature review study conducted also showed that there was limited information of thresholds of electrical conductivity (EC) levels of the recirculating nutrient solution, when refilling is absolutely needed. In addition, the tolerance of nutrient imbalances in the solution could be a crop-specific factor, as some crops could have higher ability than others, to store the nutrients that were rapidly absorbed from the solution in roots, stems or leaves, and remobilize them as needed. Similarly, the review study emphasized the importance of adjusting flow rates of the nutrient solution in NFT systems, not only for specific crops but also for specific crop management practices. For example, higher planting densities could result in slower flow rates due to denser volume of roots within the NFT pipes. Crop management aspects such as planting density, cultivar selection, pruning and suitable growing media identification are well documented for recirculating systems, particularly for those with horizontal cultivation. On the contrary, scientific information on management strategies, such as harvesting frequency, planting frequency, plant spatial arrangements, and consequent implications on water and nutritional water productivity are still limited in the literature. These aspects are important to add value and optimally reap the benefits of cultivation under the recirculating hydroponic systems. The information generated through implementation of this project assisted in narrowing such knowledge gaps.

An experiment was conducted for two consecutive growing seasons (2020-2021 and 2021-2022) at ARC-VIMP research station located in Roodeplaat, Pretoria, to test two levels of water flow rates (24 and 48 L/h) and three EC levels (1.0-1.5, 2.0-2.5 and 3.0-3.5 mS/cm) on the productivity of sweet basil, grown under a gravel film recirculating system. The study revealed that, the growth and yield of sweet basil increased with increasing EC levels. The EC levels 2.0-2.5 and 3.0-3.5 mS/cm were the best performing and comparable concentrations yielding 1.375 and 1.42 kg/plant in seasons 1 and 2, respectively. The results further revealed that 24 L/h was the best performing water flow rate with water use of 0.011 m^3 and high-water use efficiency (106.4 kg/m^3), while 48 L/h had significantly high water use at 0.020 m^3 and significant low water use efficiency (46.3 kg/m^3). The significant interactive effects have endorsed 24 L/h and 2.0-2.5 mS/cm as the best performing and efficient treatments. Identifying optimum EC level and water flow rate of the nutrient solution contribute to increased marketable yield and quality of fresh produce, income generation and profitability of farmers, while saving production inputs such as water and fertilizer. Another experiment investigated the effect of different environemntal conditions (shade net versus non-temperature controlled plastic tunnel) and plant spacing (10, 20 and 30 cm) and water flow patterns (continuous and intermittent flow) on the productivity of leafy lettuce grown in a vertical nutrient film recirculating hydroponic system. The study revealed that the interaction between environment and plant spacing significantly affected growth and yield of lettuce production. The results showed that crops grown in the tunnel at 10 cm spacing and intermittent water flow had significantly increased growth and yield (4.60 kg/m^2) compared to widely spaced crops (30 cm) grown in a shade net (0.80 kg/m^2). Furthermore, the interaction between water flow and environment significantly affected water use and water use efficiency of lettuce. Plants grown under intermittent water flow in a shade net had higher water use efficiency (0.097 kg/L) compared to continuous water flow under a plastic tunnel (0.030 kg/L). Although lettuce grown under shade net was more water use efficient, that under plastic tunnel had significantly higher yield when compared to shade net yield. Postharvest technologies developed for selected high-value vegetable and herb crops (lettuce, sweet basil and parsley), revealed that pre-harvest factors have an effect on the postharvest quality of fresh produce. The 10 cm plant spacing and anti-fog packing material were found the best for lettuce and sweet basil physical and biochemical qualities at the postharvest phase, whereas for parsley both styrofoam wrapped plastic cling film and anti-fog were comparably adequate at the 10 cm narrow plant spacing. The economic feasibility of growing high-value leafy vegetables in a vertical NFT system under a shade net versus a non-temperature controlled plastic tunnel was investigated, using leafy lettuce as an example. Results of this study revealed that lettuce production under shadenet was more viable than under plastic tunnel. This was because shadenet production had a higher net profit value than the plastic tunnel. Also, the initial investment would be recovered in a shorter period of two years. Furthermore, the project's investment would yield 30% annual rate of return over its life. Moreover, a shadenet proved more durable than a plastic tunnel, which would lead to a more profitable production in the longterm. The new knowledge generated at a research station level was subsequently transferred to farmers through establishment of the technologies on two different farmers' sites located in Zuurbekhom, Johannesburg.

This project also tested an innovative vertical bucket-column recirculating hydroponic system. The system was developed by AB Farms (a project collaborator that owned an agricultural technology company that provides innovative hydroponic turnkey solutions to farmers for increased crop productivity, while reducing the amount of land, electricity and water used per kg of fresh produce harvested). This innovative system is able to store water for root water uptake during water stress periods, unlike the conventional vertical recirculating systems which have to operate continuously. In addition, the system operates without any growing media, thus saving the farmer money, which otherwise, would have been used to pay more for electricity, water and growing media. Trials to test the performance of the technology were conducted for two consecutive growing periods (2021-2022 and 2022-2023) on leafy crops such as lettuce and sweet basil. The prototype/demonstration site was located at the Westonaria Agripark, West Rand District Municipality. In the first trial, 3600 heads of lettuce (1800 Green Oak and 1800 Red Oak) were planted in the system on the 7th December 2021 and Harvested between 4 and 7 January 2022. The shrinkage was 2.5% for the production cycle and the marketable yield was 95%, which was considered adequate. The average head weight was higher than the expected120-160 g per head. In the second trial two crops were tested, namely sweet basil and lettuce (green and red Oak leaf varieties). Sweet basil was planted using one row with eight plants placed on top of each other. A total of 1200 and 3600 sweet basil and lettuce seedlings were transplanted, respectively. The system performed very well over the experimental period. This was mostly attributed to the great advantage of the system in minimizing water stress effects on crop production, particularly during periods of loadshedding.

The information generated by implementing this project can be transferred to policy decision-makers, agricultural extension officers, as well as farmers through technology transfer dissemination outputs, such as policy briefs, farmers' days, popular articles, scientific presentations and publications. This project conducted eight local conference presentations, two radio/podcasts/interviews, five training and farmers' days events, published two book chapters, one technical report and eight popular articles, as well as four scientific publications and one educational video are currently in progress. The following new knowledge contributions were made to the scientific space through the above-mentioned technology transfer outputs: (1) optimization of production practices (water flow patterns, plant spacing, hydroponic structure, nutrient solution concentrations, postharvest packaging type and material) and economic feasibility analysis through implementation of on-station trials; (2) water productivity and nutritional water productivity of leafy vegetables grown under hydroponics; (3) an innovative vertical bucket-column recirculating hydroponic system, and (4) a gravel film recirculating hydroponic system adapted to farmers' site. Adoption of the generated technology will contribute to improved productivity of crops grown in hydroponics (both yield and nutritional content) using limited water resources, which will ultimately enhance food, nutrition and water security.

The aim and objectives of the project have been met. However, further research is warranted to expand the documentation of cost-benefit analysis on the various hydroponic technologies, test the performace of recirculating hydroponic systems on other vegetable and herb crops, develop postharvest technologies that are cost-effective and environmentally friendly and scale out the implementation of recirculating hydroponic systems, not only across the Gauteng Province, but also to other provinces of South Africa.

Apart from meeting the formulated research objectives, this project capacitated two students and two emerging commercial farmers located in the Gauteng Province. The two capacitated students were registered for a PhD degree at the University of Pretoria and an MSc degree at Tshwane University of Technology.

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LIST OF ACRONYMS AND ABBREVIATIONS

AB	Agang Bokamoso
ALVs	African leafy vegetables
ARC	Agricultural Research Council
BCR	Benefit Cost Ratio
Dr	Doctor
DWC	Deep-water culture
EC	Electrical conductivity
EM	Effective microorganism
GDARD	Gauteng Department of Agriculture and Rural Development
GFT	Gravel film technique
IRR	Internal Rate of Return
LAT	Latitude
LONG	Longitude
MGB	Media-based grow bed
NFT	Nutrient film technique
NPV	Net Present Value
P	Purified
PGPR	Plant growth promoting rhizobacteria
PVC	Polyvinyl chloride
UV	ultraviolet
VIMP	Vegetable, Industrial and Medicinal Plants
WRC	Water Research Commission

LIST OF SYMBOLS

B	Boron
C	Calcium
˚C	Degrees Celsius
$CaNO_3$	Calcium nitrate
Cu	Copper
Fe	Iron
H	Height
H_2PO_4	Dihydrogenphosphate
HCO_3	Bicarbonate
K	Potassium
L	Length
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NH_4	Ammonium
NO_3	Ammonia
P	Phosphorus
S	Sulphur
SO_4	Sulphate
W	Width
Z	Zinc

LIST OF UNITS

Kg	Kilogram
L	Litre
M	Metre
Ml	Mililitre

CHAPTER 1: INTRODUCTION AND BACKGROUND

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Active, recovery or recirculating hydroponic systems (those which rely on pumps to actively move the nutrient solution to the planting bed, with the remaining nutrients after root uptake being recovered and reused in the system) are well known for their potential to maximize crop production, resulting in increased yields and better quality of the produce (Hughes, 2019). Such systems are able to sustain crop production continuously throughout the year, using controlled environmental fluctuation techniques, thus limiting or eliminating the influence of harsh weather conditions (Okemwa, 2015). In addition, hydroponic production is generally less labor intensive, since it does not require cultural operations such as ploughing, weeding and soil fertilization (Nguyen et al., 2016). These systems can also be put up anywhere near the markets and, as a result, the fresh produce can have better marketable qualities due to reduced transportation distances, especially for vegetables which are highly perishable. Compared to conventional soil cultivation methods, hydroponic systems are generally more efficient in terms of land, water and nutrient use, and are often less susceptible to incidences of pests and diseases due to lower crop exposure to environmental stresses. In such systems, crops can be produced on non-arable land, including poor soils having high salinity levels (Rorabaugh et al., 2002).

Active, recovery hydroponic systems, such as the flood-and-drain (also called ebb-and-flow) and the nutrient film techniques, with various alterations of the basic principles utilized, are the most used worldwide. In both systems, plants are grown in well-drained inorganic substrates (rock wool, perlite or gravel), with the main difference being that in the former plants are flooded on a regular basis, while in the latter plants are exposed to a continuous recirculation of a nutrient solution, with or without an inert substrate. Recirculation of water on a regular basis as opposed to a continuous water flow, may be an advantage for improved nutritional content of the crop, especially for fruiting vegetables like tomatoes, sweet peppers and cucumbers, however, it requires a more complex system set-up, involving a timer to regulate water cycles based on crop water requirements. Both hydroponic systems can be used for either horizontal or vertical farming, with the latter often being implemented indoors, under carefully selected and well-monitored conditions.

The Agricultural Research Council – Vegetable and Ornamental Plants (ARC-VOP) has been conducting research on active, recovery (closed) and non-recovery (open) hydroponic systems for over a decade. The research findings and technologies developed were published in scientific journals and transferred to various beneficiaries, including smallholder farmers, students, and private and public sector bodies (Maboko et al., 2017; Mampholo et al., 2016;). Research on recovery or closed hydroponic systems and technology transfer to smallholder farmers is particularly important in South Africa due to the limited availability of water and land resources for agriculture. If smallholder farmers can shift their traditional methods of cultivation to economic viable hydroponic systems, they stand a better chance of developing into commercial farmers. This will result in economic growth, improved food security and poverty reduction. The field of hydroponics and vertical farming is relatively new in South Africa and, as a result, the majority of smallholder farmers are not aware of the benefits of such systems, their set-up, their operation and their management. For successful implementation of these systems, good skills and knowledge of their principles are required. The Gauteng Department of Agriculture, Rural Development and Environment (GDARDE) has supported many farmers around the province with the provision of infrastructure (e.g. tunnels, irrigation systems, production inputs, etc.) in an effort to promote and encourage farmers to adopt and practice hydroponics as a method to address food security, as well as job creation and income generation. However, due to a lack of training, financial and technical support, farmers ended up producing crops with low yields and of poor quality, with high input costs, which cannot be sustained. This resulted in the failure of most of their farming operations, whereby farmers ended up either abandoning hydroponic farming or opting for conventional soil cultivation practices.

Locally developed recovery hydroponic systems, such as the gravel-film technique and simple vertical farming structures can be modified or adapted to suit the farmers' needs through training and technology exchange. Therefore, the proposed project aimed at conducting training and the exchanging of practical knowledge on active, recovery hydroponic systems for the production of vegetables and herbs on smallholder farms in the Gauteng Province of South Africa.

1.1 Problem statement

The field of hydroponics and vertical farming is relatively new in South Africa and, as a result, the majority of smallholder farmers is not aware of the benefits of such systems, their set-up, operation and management. For successful implementation of these systems, good skills and knowledge of their principles is required. Although the Gauteng Department of Agriculture and

Rural Development (GDARD) has provided support to farmers around the province with hydroponic infrastructures, as an effort to promote and encourage farmers to adopt and practice hydroponics as a method to address food security and poverty alleviation, these farmers are still struggling to maintain sustainable hydroponic productions. Morifi et al. (2018), who conducted a detailed study on how sustainable the training of hydroponic production to smallholder farmers is in the Gauteng province, have identified the following factors as major reasons for lack of sustainability: (1) high initial and operational costs and (2) appropriate skills and knowledge as a requirement for smallholder farmers to operate hydroponic systems adequately. As a result, this project aimed to provide training and exchanges of practical technology of relatively simple closed hydroponic systems for vegetable production in smallholder farms of the Gauteng province, in South Africa.

1.2 Rationale

The knowledge generated through the implementation of this project will contribute to knowledge and skills transfer to smallholder farmers in the Gauteng Province of South Africa, on recirculating hydroponic systems' set-up, operation, management and maintenance. This will ensure a more successful implementation of these systems, which will contribute to improved crop productivity (marketable yield and quality) and increased farmers' profitability, with the use of lower inputs of water and nutrients into the system. This will result in: (1) money savings, as lower amounts of fertilizer will be required; (2) more sustainable production as the result of reduced water usage; (3) environmental protection due to elimination of drainage and leaching of nutrients, as well as runoff losses. Hydroponic systems can be set-up anywhere, which offers great potential for crop production to be carried out closer to the market, leading to reduced transportation costs and improved marketable quality of the produce due to reduced transportation distances. This is particularly important in vegetable production, as these are highly perishable.

1.3 Aim and objectives of the study

This project aimed to provide training and exchanges of practical technology of relatively simple closed hydroponic systems for vegetable production in smallholder farms of the Gauteng province, in South Africa. The following objectives were formulated:

- Understand the state of hydroponics and urban farming in Gauteng and its potential to form part of mainstream commercial agriculture (in terms of total available market and serviceable market) and to solve environmental problems (in the context of water/energy/food nexus);

- Understand the needs and goals of selected smallholder farmers in the field of crop production, as well as their past experiences with the implementation of conventional soil versus hydroponic production systems;
- Test the operation, determine optimal operating parameters and conduct cost-benefit analysis of selected active, recovery hydroponic systems (gravel-film horizontal system, nutrient-film vertical system and hydroponics planter vertical system);
- Evaluate optimum performance practices at farmers sites, with farmers participatory intervention;
- Modify or adapt components of the technologies tested based on farmers needs and local conditions for increased adoption and successful operation;
- Develop educational materials on the use of active, recovery hydroponic systems.

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CHAPTER 2: REVIEW OF LITERATURE ON RECIRCULATING HYDROPONIC CROP PRODUCTION

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2.1 Introduction

Research on recovery or closed hydroponic systems and technology transfer to smallholder farmers is particularly important in South Africa due to the limited availability of water and land resources for agriculture. If smallholder farmers can shift their traditional methods of cultivation to economically viable hydroponic systems, they stand a better chance of developing into commercial farmers. This will result in economic growth, improved food security and poverty reduction. The field of hydroponics and vertical farming is relatively new in South Africa and, as a result, most smallholder farmers are not aware of the benefits of such systems, their set-up, their operation and their management. For successful implementation of these systems, good skills and knowledge of their principles are required. The Gauteng Department of Agriculture, Rural Development and Environment (GDARDE) has supported many farmers around the province with the provision of infrastructure (e.g. tunnels, irrigation systems, production inputs, etc.) to promote and encourage farmers to adopt and practice hydroponics as a method to address food security, as well as job creation and income generation. However, due to a lack of training, financial and technical support, farmers ended up producing crops with low yields and of poor quality, with high input costs, which cannot be sustained. This resulted in the failure of most of their farming operations, whereby farmers ended up either abandoning hydroponic farming or opting for conventional soil cultivation practices. This study comprises of a comprehensive literature review on past knowledge of active recovery hydroponic systems. Gaps in the current knowledge were identified and recommendations for future research were made.

2.2 Methods used for literature search

An integrated qualitative systematic approach was used in this study to search, select and manage the best available knowledge relating to active recovery hydroponic systems. This was integrated with the authors' expertise in this field to thoroughly discuss the most relevant topics to identify the current gaps in knowledge and to provide appropriate recommendations for future research to address these gaps. The literature search included online sources, peer reviewed papers published in scientific journals, books and other publications such as popular articles. Published literature from universities, national research institutions, in the form of student theses and dissertations, conference proceedings, working papers, and project reports were also considered. A detailed literature search was conducted using various search engines such as Google, and the University of Pretoria's and the Agricultural Research Council's online databases.

Approximately 400 literature sources were retrieved, of which 55% were read through based on their relevance to the subject of research. These literature sources were analyzed and are cited in this study. The search was facilitated by guiding key words and terms. Thus, a total of 220 literature sources are cited. Seventeen percent of these sources are related to the theory and principles of hydroponics or soilless culture, including the different types of systems available, their classification, advantages and disadvantages. Thirty five percent of the cited sources are associated with hydroponic structure characteristics (with controlled and non-controlled environmental conditions) and their suitability for implementation of the different active recovery hydroponic systems and crops produced. For this specific purpose, the relevant literature was sought from publicly available published ISI journal papers, in electronic archives, that reported on crop-based experiments and/or production systems that utilized water cultures. Many potential papers were identified, but only those that indicated or provided information that made it possible to discern if the structures were non-controlled or controlled were used. Thus, a total of 78 papers met the selection criteria and were used to build two datasets. The first dataset consisted of 11 papers that reported on non-controlled systems, while second dataset consisted of 67 papers that reported on controlled systems. The datasets were analysed using simple statistics. Some of the primary data collected from the papers were categorized into factor classes in order to facilitate the analyses. The remaining 48% of the literature sources cited in this review are related to the management of active recovery hydroponic systems (90 papers) and crop production (52 papers).

From the total number of 220 literature sources cited in this review, 150 were peer-reviewed scientific articles (68%), 30 were conference proceedings (14%), 25 were technical reports (11%), 10 were theses and dissertations (5%) and 5 were books (2%). Ninety-seven of these papers (44%) were published between 2014 and 2020, 24 between 2008 and 2013 (11%), 40 between 2000 and 2007 (18%), while the remaining 59 papers (27%) were published before 2000. The literature review document was checked for plagiarism using the plagiarism checker software "Grammarly", which revealed a plagiarism value of 19%, which is within the acceptable level for scientific writing (Stapleton, 2012).

2.3 An overview of hydroponics and soilless culture

2.3.1 Concept of hydroponics

Due to a rapidly growing population, there is an increased competition for industrial and residential land and a significant shortage in the amount and quality of irrigation water as well as arable land for agricultural purposes. The increasing pressure on land and natural resources emphasize the need for innovative ways of increasing production with limited resources (Niederwieser and Du Plooy, 2014). Agricultural scientists have developed techniques to address this need, and hydroponics is one of the methods which can be used in this regard.

Hydroponics is simply referred to as a method of growing plants under soilless conditions or without soil, which uses nutrient solutions to irrigate the plants (Niederwieser and Du Plooy, 2014). The word hydroponics comes from the two Greek words, *hydro* meaning water and *ponos* meaning labour, i.e. plants growing in water (Jones, 1997). Many use the term to refer to systems that do include some kind of growth media to anchor the plant and to provide an inert matrix to carry water. However, hydroponics is the practice of growing plants in nutrient solutions with or without the use of an artificial growing medium and can be divided into two categories, liquid hydroponics and aggregate hydroponics. Liquid hydroponic systems do not have supporting mediums for the plant roots, while aggregate systems have a supporting medium for the plant roots (Jensen, 1997). Thus, production systems with inert growth media, such as stone wool or gravel, are considered to be hydroponic production systems. The growing media are needed to provide support to the plant, hold water and nutrients for the plants (depending on the water holding capacity of the medium), as well as to block out direct sunlight to the plant roots and the nutrient solution.

In the beginning, researchers used hydroponics only to investigate certain aspects of plant nutrition and root function. However, progress in plastics manufacturing, automation, production of soluble fertilizers, especially the development of different kinds of growth media, complemented the scientific achievements and has brought hydroponic farming methods to a viable commercial stage. Today several different types of hydroponic systems exist for growing vegetables and ornamentals in greenhouses.

2.3.2 Advantages and disadvantages

With the implementation of hydroponic systems, it is possible to achieve maximum crop yields, making the systems economically feasible using high-value commercial crops, which are cultivated at high planting densities, even in less favorable production areas (Jones, 1997). In addition, since hydroponic systems operate under protected environments, a virtual indifference to ambient temperature and seasonality is possible; the systems make use of minimal land area and are suitable for mechanization and disease control. The main advantage of hydroponics, as compared to planting in soil, is the isolation of the crops from the underlying problems related to soil-borne diseases, soil salinity, and poor soil structure and drainage. The expensive and laborious tasks of soil sterilization are unnecessary in hydroponic systems and a rapid turnaround in the production of crops is readily achieved. Hydroponics offers a means of control of soil-borne diseases and pests, which is particularly problematic in the tropics, where infestations are a major problem. Hydroponics also has the ability to provide plants with all of the required nutrients in the correct ratios throughout the growing season, there is little or no weed control and the harvested produce is free of soil particles (Niederwieser and Du Plooy, 2014). In addition, with hydroponics good quality produce is obtained with more efficient utilization of water, enabling the grower to manipulate some of the plant characteristics to meet consumer demands. Table 2.1 illustrates a comparative performance between soil and soilless production of lettuce and brassicas using hydroponics. The assessment was conducted in terms of crop yield obtained, water and energy requirements per kilogram of the harvestable produce. Results indicate that, hydroponic production (particularly under vertical systems) has considerably higher potential for increased crop productivity due to higher number of plants cultivated per m^2 and substantially lower water usage (66-100 times lower) when compared to soil crop production (Van Ginkel et al., 2017). Thus, as Sambo et al. (2019) reported, the water use efficiency (WUE) of crops grown in hydroponics varies from 7.3-630 kg m^3, which is substantially higher when compared to that under soil crop production (1.8-13.2 kg m^3).

Table 2.1: Comparative performance between soil and soilless hydroponic production of leafy vegetables, in terms of crop yield, energy and water usage (Van Ginkel et al., 2017).

Parameter	Soilless hydroponic production in shipping containers		Soil production	
	Lettuce	Brassicas	Lettuce	Brassicas
Plants per m^2	1305-1371	432	39	10
Crop yield ($kg\ m^{-2}\ yr^{-1}$)	193-202	64	7	3
Energy ($kWh\ yr^{-1}$)	115283	115257	2948	2757
Energy ($kWh\ kg^{-1}$)	19	61	0.20	0.45
Water ($L\ kg^{-1}$)	1.6	5.0	106	507

Despite the numerous advantages described above, the system has a few drawbacks. The major disadvantages of hydroponics relative to conventional open-field agriculture include high investment costs, high degree of knowledge and management skills required for successful operation and production, as well as high energy inputs. Energy consumption in hydroponics can be as high as 95-136 times more than conventional soil cultivation as illustrated in (Table 2.1 Van Ginkel et al., 2017). This is particularly evident in fully environmental controlled greenhouses like shipping containers, where high energy usage is mainly attributed to the artificial lighting, heating and cooling requirements. Capital costs may be especially excessive if the structures are artificially heated and/or cooled by fan and pad systems. Also, systems of environmental control are not always needed in the tropics (Jensen, 1997). The system uses soluble fertilizers, which are more expensive than those used for open field production and lastly, there is a very limited variety of crops which can be grown profitably in a hydroponic system.

2.3.3 Classification of hydroponic systems according to different aspects

2.3.3.1 Nutrient solution supply mechanism

Based on the nutrient solution supply mechanism, hydroponic systems can be classified as passive and active systems. Passive hydroponic systems are those systems that provide the nutrient solution beneath the plant roots, in which the plants are either suspended over a nutrient solution and nutrients are taken up by the roots that are partly immersed in water (Figure 2.1a), or the plants are anchored in a growing media and a wick is used to transport the nutrient solution to the media via capillary action (Figure 2.1b) (Sheikh, 2006). The first type of passive hydroponics is called deep-water culture (DWC) or floating system/ Kratky method, while the second type is termed wicking system. In the DWC technique, plants are placed in net pots, with the root system partly suspended in a nutrient solution, where they grow quickly in a large mass. It is necessary to monitor the oxygen and nutrient concentrations, salinity and pH, since algae and mold scan grow very quickly in the reservoir. This system works well for larger plants that produce fruits, especially cucumber and tomato grow well in this system (Domingues et al., 2012). Passive hydroponic systems do not use pumps or timers to flood the root zone. The plant roots are usually dangled or suspended into the nutrient solution and rely on its roots to access the nutrient solution. In this system, once plants absorb the nutrient solution, the water surface decreases, and exposed roots with fine root hairs develop in the air above the water surface. Thus, the roots can absorb oxygen directly from the air (Sheikh, 2006).

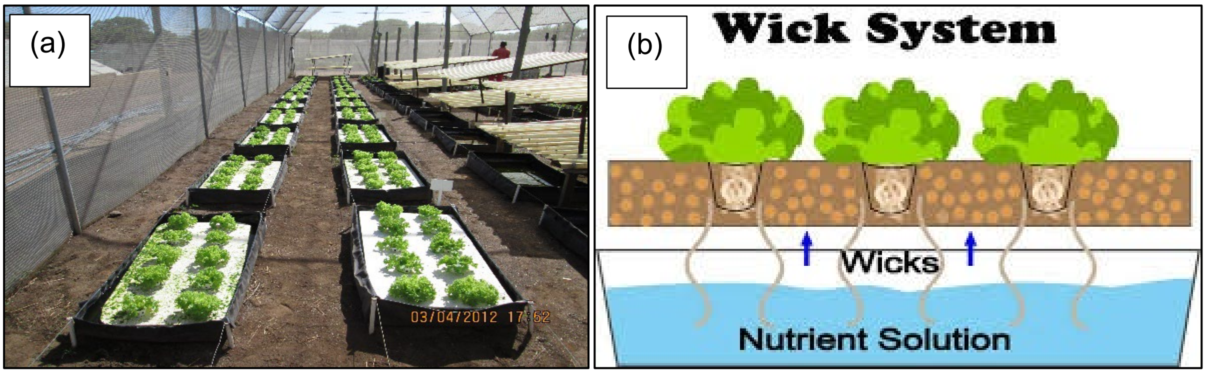

Figure 2.1: Types of passive hydroponic systems: (a, picture taken by TS Chiloane) deep-water culture (also called Kratky method) and (b, https://smartgardenguide.com) wicking system.

Active hydroponic systems on the other hand, are those systems that rely on pumps and other mechanical devices to actively move or pump the nutrient solution to the roots (Jones, 1997; Roberto, 2003). The systems comprise of different types of techniques which are categorized as open and closed systems, based on their mechanism of drainage of the nutrient solution, as described in the following section.

2.3.3.2 Drainage of the nutrient solution

Based on the drainage of the nutrient solution, hydroponic systems can be classified as recovery (also called closed) and non-recovery (also called open) systems. Recovery systems refers to those systems where the nutrient solution is recovered, recycled or reused back into the system (Jensen, 1997). Non-recovery systems on the other hand, are those systems whereby, once the nutrient solution is pumped and delivered to the plant roots, it is not recycled or reused (thus, it drains out as waste).

Non-recovery hydroponic systems, with a typical example being the open bag technique, are the most used systems in South Africa for the production of fruiting crops such as tomatoes, peppers and cucumbers. This kind of hydroponic system typically has two main parts, a plant container, and a nutrient supply system that supplies nutrients and water to the plants. It is important that the proper amount of nutrients, which are normally in water, are supplied to the plants. However, if too little solution is supplied to the plants, they will die or develop deficiencies, and if too much is supplied it may cause toxicity or burn the plants (Gutridge, 1990). Therefore, it is important that a nutrient supply mechanism for a hydroponic system is able to provide enough nutrient solution to feed the plants and at the same time accurately measure the amount of nutrient solution to ensure that an adequate amount of nutrients are supplied to the plants.

In the open bag technique, plants are grown in containers (usually plastic bags) filled with a growth medium. In South Africa, sawdust is commonly used as a substrate or growth medium in 10-15 L polyethylene bags, with drainage holes near the bottom of the bag. The containers are placed directly on to the greenhouse floor and the floor is generally covered with white polyethylene sheeting to isolate the system from soil-borne diseases and to prevent plant roots from growing into the soil. White polyethylene sheeting also serves to reflect sunlight back on to the plants. One or more plants are planted in each bag or container and an irrigation system is installed to supply the nutrient solution to each container. The containers are free to drain, usually from the base, and surplus nutrient solution runs to waste through overlaps in the polyethylene sheet. It is advisable to have reservoirs to collect the surplus nutrient solution in order to prevent contamination of the ground water. A drip irrigation system is normally used with the open bag systems. Each plant is fed individually, using a drip feed line placed on the bag and into the substrate. The irrigation line runs the length of the rows between each set of two rows of bags. The nutrients are then pumped from a central injector system into the main irrigation line using a stock solution tank. With the open bag system, care should be taken that salts of the nutrient solution do not accumulate or build up in the medium as it can affect plant growth. One way of monitoring this is to irrigate with about 10-20% more water in order to flush out excess salts in the medium (Niederwieser and Du Plooy, 2014; Maboko and Du Dlooy, 2013).

Some of the main advantages of the open bag culture system (non-recovery system), with sawdust as the growing medium, implies that the spread of root rot diseases is less than with re-circulating systems, that there is good lateral movement of the nutrient solution throughout the root zone, that there is good aeration in the root zone, and a fresh nutrient solution is added with each irrigation (Jensen, 1999; Niederwieser and Du Plooy, 2014). The system is easy to repair and maintain because the fittings can be easily replaced. The relatively high water retention of the sawdust and other media reduces the risk of rapid water stress should a pump fail. Sawdust is also relatively inexpensive, since it is readily available in South Africa (Niederwieser and Du Plooy, 2014).

Disadvantages of an open bag culture system with sawdust as the growing medium includes the fact that some types of sawdust and other organic media contain chemicals that are toxic to plants and therefore chemical analysis should be done whenever a new batch is purchased over the cropping season. Also, salt accumulation can occur in the medium to levels that are toxic to plants, clogging/blockages of drippers may occur if proper filters are not used, and if the sawdust is very coarse, coning of the nutrient solution may occur. This can be controlled by spreading a thin layer of fine sand on top of the sawdust. Lastly, since sawdust is an organic medium and decomposes over time, it is usually replaced after one growth season, thereby increasing the cost of production or input costs (Jones, 1997; Niederwieser and Du Plooy, 2014).

Recovery or recirculating hydroponic systems are gaining more popularity lately, not only in South Africa, but all over the world (Maboko et al., 2011). The major advantage of these systems is the ability to reuse the drained nutrient solution after circulation through the plant roots. This contributes substantially to water and nutrient savings (Bar-Yosef, 2008). In addition, these systems allow for vertical cultivation of vegetables, which maximizes the utilization of land or space (Touliatos et al., 2016). These hydroponic systems often use small amounts of substrate or growth medium to anchor the plant into the system, as well as for early development of seedlings/cuttings prior to transplanting into the system (Mattson and Lieth, 2019).

2.3.3.3 Support media for plant roots

Plants in hydroponics can be supported through various growing media, as long as they meet the following qualities: (1) sufficient support for the plants; (2) appropriate distribution of air, since roots need oxygen and respire other gasses, such as carbon dioxide; (3) sufficient water availability for the plant roots; and (4) an accessible nutrient solution with consistent chemical characteristics. Thus, based on growing media used for supporting of the plants, hydroponic systems can be classified as aggregate and non-aggregate (also called liquid) systems.

Aggregate systems comprise those involving a solid, inert medium to provide support for plant roots. These systems may be either open or closed, depending on whether surplus amounts of the nutrient solution are to be recovered and reused. Open systems do not recycle the nutrient solutions, while closed systems do (Maboko and Du Plooy, 2013). A typical example of an aggregate open system is the open bag technique (Figure 1.2). They are used for the production of indeterminate, high value fruiting crops like tomatoes, peppers and cucumbers. Any crop that grows at least 1 m high is suitable for the bag system. Bag culture systems are relatively cheap to install and operate, but have a higher maintenance and running cost as compared to closed hydroponic systems.

Figure 2.2: Tomato plants grown using an aggregate open hydroponic system-open bag technique using sawdust as the growing medium (picture taken by TS Chiloane).

In the bag culture system, the bags are filled with a growing medium such as sawdust, cocopeat/coir, perlite or sand. The bags have holes either on the side or underneath the bags. It is normally recommended that the holes be placed on the side of the bag, so that a small amount of water can serve as a reservoir during periods when water is limited or during power failures. It is important to place the irrigation dripper next to the stem of the young seedling so that the seedling receives water immediately because the root system would still be underdeveloped. Placing the irrigation dripper too far away from the seedling will prevent the water from reaching the roots of the seedling (Maboko et al., 2012).

In hydroponics, the substrate replaces the soil, not to provide nutrients, but to anchor plant roots which carry the plant's weight and hold it upright. Almost any inert material can be used as a growing medium. Inert refers to material that can't/won't decay or break down rapidly. Hydroponic substrates are simply soilless material that are generally porous so that it can hold water and oxygen that the root system requires to grow and develop. Nonporous materials can be used as well, but watering cycles would need to be more frequent so the roots don't dry out between irrigations (Jensen, 1999). The growing medium on its own, irrigated with water only, will not support the growth of plants and the plants will develop nutrient deficiencies. The growing medium is simply there to help support the plant, as well as to hold moisture and nutrients in support of plant growth supplied through the irrigation system (Mattson and Lieth, 2019).

Some of the most widely used growing media include sawdust, rockwool, cocopeat/coconut fibre/chips/choir, perlite, vermiculite and peat moss. While there are many materials which can be used as substrates in hydroponics, they all have different characteristics. There is no one growing media that is better than another, and it mostly depends on the type of hydroponic system that is being used. There are many aspects to consider when choosing the growing media, as described below.

Rockwool (Figure 2.3a) has been used widely, largely on commercial farms (Roberto, 2003; Sheikh, 2006). It has been proven to be very effective, and hence its popularity. This sterile, porous substrate is made up of granite and/or limestone rocks which are heated until melting and then are spun into very thin and long fibers. Thereafter, the fibers are compressed into cubes and bricks of preferred sizes. Rockwool has many benefits making it an excellent growing substrate such as microbe immunity, and has good water and air retention. This protects plants from drying out, while supplying plant roots with sufficient oxygen. However, the natural pH of rockwool is usually high, which can alter the pH of the nutrient solution. This can be prevented by soaking the media in pH balanced water before it is used. Rockwool is non-degradable and therefore it is not environmental friendly (Mattson and Lieth, 2019). The unused fibers of rockwool are almost unable to be disposed of and the dust given off from the medium can cause irritation of the lungs and eyes. Therefore, it is a good practice to wet it with water before using it.

Vermiculite (Figure 2.3b) is a form of hydrated laminar minerals, which resembles mica, and just like perlite, vermiculite is processed by exposing the material to extreme heat to expand it into small clean, odorless pellets. The medium is non-toxic, sterile, very lightweight and has better water holding capacity compared to perlite. This growing media also has a reasonably good cation-exchange capacity, which helps in retaining of nutrients for later use. There are different types of vermiculite, but because of its ability to retain a lot of water (approximately 200%-300% of its weight), there is a risk of suffocating the plants (Jones, 1997; Jensen, 1999). Plants breathe through their roots and when there is too much water, the roots cannot take in gases, resulting in suffocation of the plants. Therefore, it is generally mixed with other substrates when used. The most common substrate with which it is mixed is perlite, since the two media complement each other very well. Perlite drains very fast, whereas vermiculite retains moisture. They are usually mixed at a ratio of 50/50, which normally prevents the mixture from being washed out in ebb-and-flow systems (Robert, 2003; Sheikh, 2006).

Perlite (Figure 2.3c) is a very common growing medium that has been around for years and is usually used by traditional gardeners to enhance aeration of soil mixes. Perlite is a mined material. Perlite is a volcanic glass that is heated to about 1000 ºC whereupon it pops much like popcorn and expands to 13 times its former size, resulting in an incredibly lightweight and porous material. Perlite is a good medium for the wick-type hydroponic system. But, because of its porosity and easy-to-flow nature, it is not recommended for use with rapid and strong watering systems like the ebb-and-flow system. It can be rapidly and easily washed away, it has the ability to hold air very well and it also has a neutral pH. Perlite is rarely used alone and is often mixed with other growing media like vermiculite and cocopeat/coir. The most common combination is with vermiculite at a ratio of 50/50 (Robert, 2003; Mattson and Lieth, 2019).

Sawdust (Figure 2.3d) is a by-product of sawmills and retail hardware stores and it is quite inexpensive. This material is lightweight and it retains water well (Jones, 1997). Sawdust is biodegradable, therefore, it will decompose over time. Even after composting, sawdust decomposes faster than bark, and therefore a greater amount of nitrogen is tied-up in the medium. Fresh sawdust needs immediate addition of nitrogen for microbes to break down the exposed soluble carbohydrates. It must be treated with an alkaline substance as potassium hydroxide to remove or dissolve the sugars. Wood fibers have very little buffering capacity and have no real influence on the pH of the nutrient solution mix. Wood shavings and sawdust from some tree species are toxic to plants, and these should therefore not be used. In South Africa, sawdust is the most common and readily available substrate, particularly in forested areas of the Mpumalanga and KwaZulu Natal Provinces (Niederwieser and Du Plooy, 2014). Untreated sawdust is relatively cheap, but this sawdust needs to be analyzed for chemical and physical properties beforehand. Fine sawdust or sawdust mixed with wood shavings gives a better lateral movement of water than the coarser grade of sawdust. Sawdust has a problem of algae build-up when moist, and can only be used for 10-12 months, after which it has to be replaced (Maboko et al., 2012; Niederwieser and Du Plooy, 2014).

Peat moss (Figure 2.3e) is an excellent moisture and nutrient retaining medium and is also an organic soil-softening durable material (Jones, 1997). Peat moss is a dead fibrous material that forms when sphagnum mosses and other living material decompose in peat bogs into a deep dark brown material. Peat bogs are wet, cold, acidic, and anaerobic environments. This process of decomposition can take place over a few thousands of years. Therefore, peat moss is not considered a renewable medium and it is not environmentally friendly. This is a good medium for soil and hydroponic systems because of its ability to hold water and nutrients very well. When peat moss gets wet, dehydrates quickly and does not compact or break down easily, and thus has a life cycle of several years. The medium does not contain weed seeds or microorganisms, unlike other organic composts. It can be blended with perlite, vermiculite, or styrofoam particles to increase aeration and to adjust the pH of this medium (Robert, 2003; Sheikh, 2006).

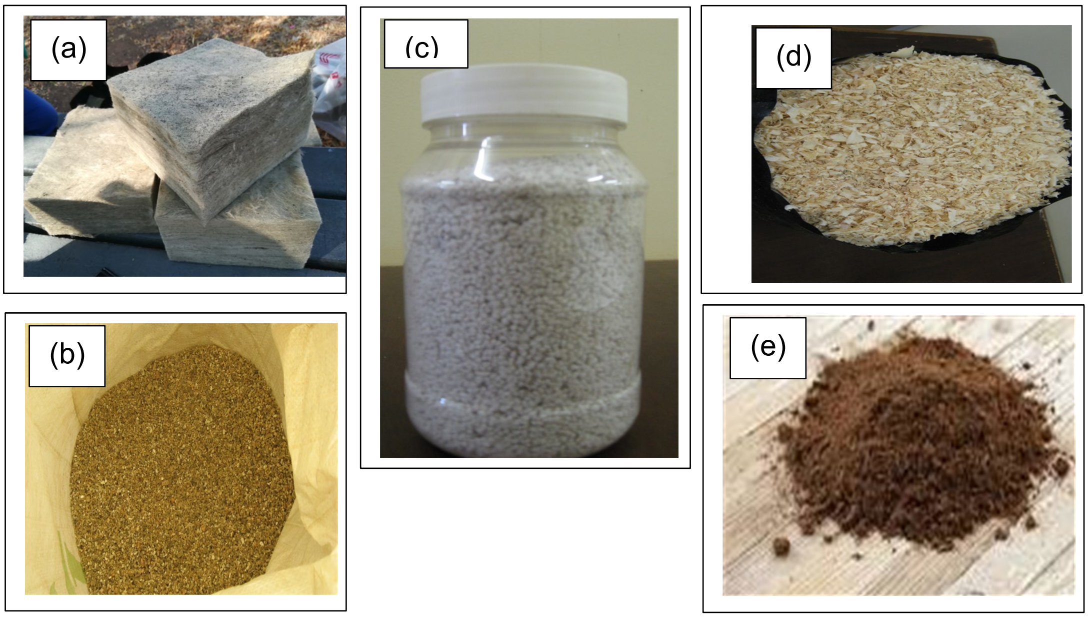

Figure 2.3: Different growing media used in the open bag culture aggregate hydroponic system: (a) rockwool; (b) vermiculite; (c) perlite; (d) sawdust; and (e) peat moss. Picture (d) was taken by TS Chiloane, while others were extracted from https://www.shutterstock.com

Non-aggregate systems, also called liquid systems, are those in which plants grow in a water solution, without the use of any solid substrate (Mattson and Lieth, 2019). The key in this type of plant production system is that the water contains nutrients and oxygen at levels that lead to high rates of plant development. In these systems, water flows through the root zone during irrigation events. During this movement of water, the nutrient molecules dissolved in the water move at speeds that are several orders of magnitude greater than the diffusion processes (Jones, 1997; Mattson and Lieth, 2019), and this kind of movement is called “bulk flow.” A key factor of all hydroponic systems is that bulk flow is used widely to transport nutrients and therefore the root surfaces are exposed to more of these nutrient solutions. Furthermore, these flow rates are so much faster than typical hydroponic nutrient solutions and can be much more diluted than conventional irrigation nutrient solutions, yet still allowing the plants to take up more nutrients. These lower nutrient solution concentrations have lower electrical conductivity (EC) levels (less salinity), which can be very beneficial to plant growth. One facet of liquid culture systems is that it is important to minimize the amount of nutrient solution that is exposed directly to light (Mattson and Lieth, 2019). This can be done by using growth trays that are not transparent or do not have the ability to reflect radiation or the incident light. In addition, the nutrient solution beneath the plants should be covered as much as possible to avoid incident light reaching the nutrient solution. Growth of algae develops in the system if light is not restricted, since the nutrient solution provides optimal conditions for the growth of algae. It is unavoidable that some algal growth will be present in nearly all systems (Mattson and Lieth, 2019). The detrimental effects of algae are that: (1) the algae takes up the nutrients and oxygen that are meant for the crop and thus competes with the crop; and (2) the proliferating cells will result in the production of unattractive sludge that could block some components of the system, like filters and drippers (Mattson and Lieth, 2019). In South Africa, the most popular aggregate recovery systems are the ebb-and-flow (Figure 2.4a) and the gravel-film techniques (Figure 2.4b). The most common non-aggregate recovery systems are the nutrient film technique (NFT) (Figure 2.4c) and the deep-water culture or floating system (Figure 2.4d) (Niederwieser and Du Plooy, 2014; Maboko et al., 2011).

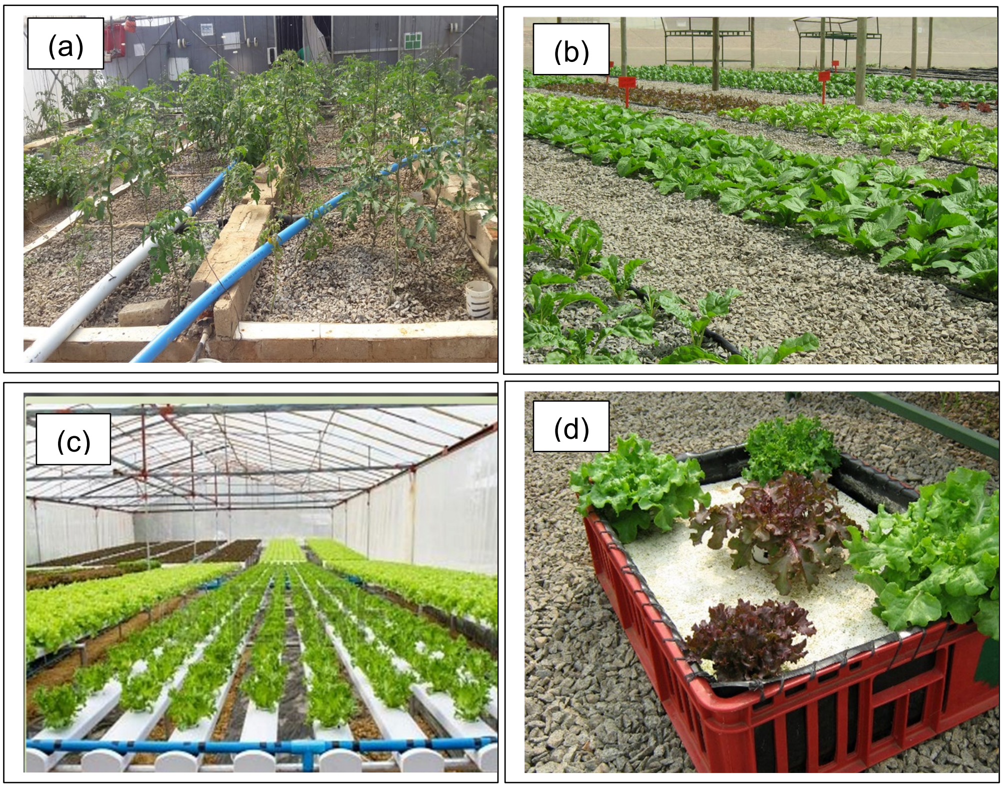

Figure 2.4: Aggregate recovery hydroponic system examples using gravel as the growing medium: (a) the ebb-and-flow technique; and (b) the gravel-film technique. Non-aggregate recovery hydroponic system examples: (c) the nutrient-film technique with horizontal cultivation; and (d) the deep-water culture technique. Pictures taken by NA Araya and TS Chiloane.

2.4 Commonly used active, recovery hydroponic systems

2.4.1 Media-based grow bed (MGB)

2.4.1.1 Design characteristics

These systems are simple to operate and the nutrients are stored below the tray used for plant growth or in a tank. A pump is submerged into the nutrient solution which, when switched on, pumps the nutrient solution up to the plant tray and floods the root system for nutrient uptake. After running the pump for about 20 or 30 minutes, it is switched off and the excess solution is allowed to drain slowly back into the reservoir for recovery (Figure 2.5). A typical example is the ebb-and-flow system. Not only does this supply the plant with all the nutrients that it needs, but the removal of nutrients after flooding will pull oxygen down to the roots, further promoting proper plant growth (Nicola, 2007).

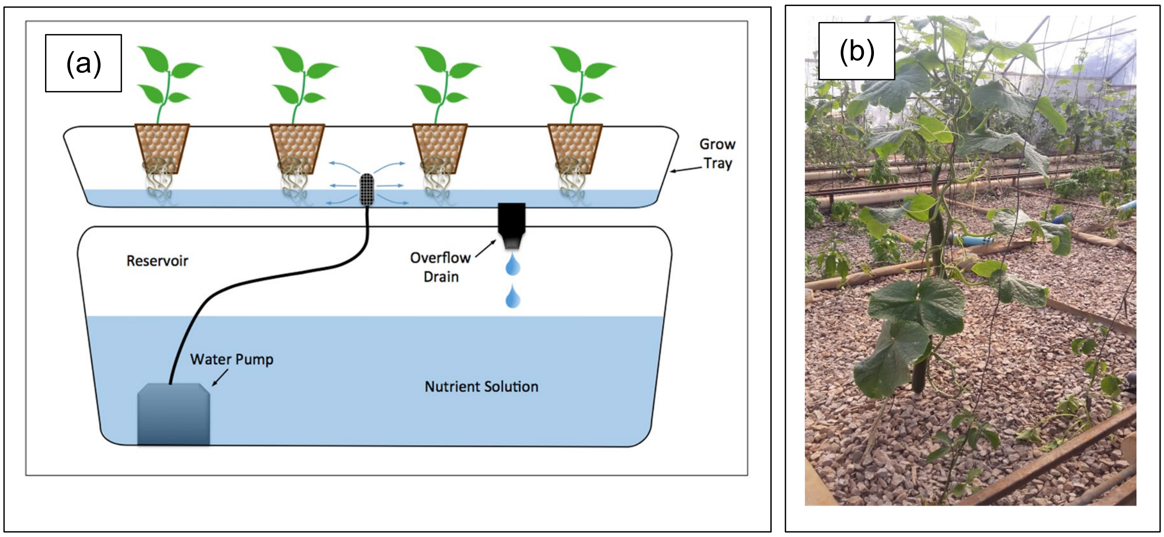

Figure 2.5: The ebb-and-flow system design (a, https://www.aquaponics4you.com) and cultivation of cucumbers using the ebb-and-flow system (b, picture taken by NA Araya).

The ebb-and-flow hydroponic growing system has been widely used for many years, although it is not commonly used commercially today, other than for hobby/home-type growing units. This system is also called the "flood and drain" system (Figure 2.5). The growing system consists of the following components: (1) a watertight rooting bed containing an inert rooting medium, such as gravel, coarse sand, or volcanic rock; (2) a nutrient solution sump (equal in volume to the growing bed); (3) an electrical pump for transporting of the nutrient solution from the tank to the growing bed, and (4) a piping system to cater for the delivery of the nutrient solution from the tank to the growing bed and its return to the tank (Nicola, 2007). In order to have the nutrient solution return through gravitational flow from the growing bed into the tank, the sump must be below the growing bed. Since this is a "closed" or recirculating system, the nutrient solution is recirculated until it is' no longer usable, and replaced with a freshly made up nutrient solution. Prior to each use, the nutrient solution should be tested for pH and EC and then adjusted accordingly, as discussed in Section 2.7 (Niederwieser and Du Plooy, 2014; Li et al., 2018). The nutrient solution may also need filtering after each circulation through the growing bed. The frequency of flooding of the growing bed is dependent on the atmospheric demand and growth stage of the crop, as well as the water retention ability of the substrate (Jones, 1997). The gravel film technique (GFT) is another type of MGB system widely used in South Africa, where the solution flows down the beds by gravitation (Maboko and Du Plooy, 2012) (Figure 2.6).

Figure 2.6: Gravel film technique in which leafy lettuce is being grown (picture taken by TS Chiloane).

In the GFT system, the nutrient solution is pumped to the top of the hydrolines and flows down by gravity in a thin layer (1-3 mm), creating a good balance between the required oxygen and water (Maboko and Du Plooy, 2013). The nutrient solution is collected at the bottom and pumped to the top again using a pressure pump. The areas prepared for gravel systems should be completely levelled across the slope before the hydrolines are laid out. Folding a plastic sheet over a secure tightened steel wire should strengthen the sides of the gullies. The plastic sheeting used depends on the availability and the market price. Normally a plastic sheet thickness of 50 micron will be sufficient, but it is not very durable. Using a plastic sheet thickness of 100 micron or even thicker will strengthen the hydrolines and will not be punctured very easily (Maboko and Du Plooy, 2012). The hydrolines should be at least 6 cm deep for optimal growth of crops with a shallow root system such as lettuce (Figure 2.6). For crops like tomatoes that have a large root volume, a deeper gully is recommended (Niederwieser and Du Plooy, 2014). Sand and gravel are the most commonly used growing media in these systems.

2.4.1.2 Growing media types

Gravel is the most common type of growing media in MGB systems and is used to support plants only and to block out sunlight at root level (Maboko et al., 2017). Sand is an alternative medium used in MGB systems. Sand is rock that has been eroded for some time. It occurs naturally and when rocks are eroded for long enough, they get smaller in size, and moisture does not drain out as fast. When using sand as a growing medium, it is important to use the largest grain size so that it will help increase aeration to the roots by increasing the size of the air spaces between the particles of sand. Sand can serve as a good medium for use on recovery systems like the ebb-and-flow system or the GFT. However, it must usually be cleaned or sterilized before use (Jones, 1997; Niederwieser and Du Plooy, 2014).

Gravel has been in use quite early with great success. The popular systems that use gravel as the growing medium are the gravel-based ebb-and-flow and the gravel film techniques (Lennard and Leonard, 2006; Nicola, 2007). As fragmented media from hard-wearing rocks, like sandstone, limestone, or basalt, the spaces between each particle are quite large and this gives a plentiful supply of oxygen to the roots. But, at the same time, this means that the medium doesn't hold water very well, which can cause the plant's roots to dry out quickly. Because gravel is a loose aggregation of rock fragments, its weight makes a gravel-based system very heavy to carry, but it is durable and can be reused as long as it is washed and sterilized (Niederwieser and Du Plooy, 2014; Maboko and Du Plooy, 2012).

2.4.1.3 Advantages and disadvantages

In growing-media based systems, the use of a solid, inert media provides support. The ebb-and-flow system is relatively easy to install and to operate on a small scale and gives fairly good plant performance with a moderate level of care. Nutrients are in an abundance for plants and the system ensures that the plants obtain just enough nutrients. The overflow tube ensures that flooding in the containers is not possible and therefore plants grow to maturity, and are healthy and nutritious (Jung et al., 2015). The system is easy to use once the set-up is complete and it requires minimum supervision and maintenance. The simple tasks are ensuring the availability of a nutrient solution and frequent monitoring to confirm functionality. There is very little need for technical assistance in using the system (Nicola, 2007.).

The disadvantages of this system are susceptibility to root diseases and inefficient use of water and nutrients, and commercially the system has also proven difficult to manage. With time, plant roots grow into the pipes that deliver and return the nutrient solution to and from the growing bed(s) and sump, thereby restricting the flow (Nicola, 2007). One diseased plant in the system will result in a complete loss of the entire crop. As a result, frequent removal and replacement of the gravel rooting medium is recommended. Another challenge with this system is that the sump and nutrient solution will have a temperature like that of the surrounding soil because they are set-up on the ground. This means that during most of the season, the nutrient solution will be colder than the ambient air temperature, an undesirable trait that would harm plants when the nutrient solution has been dispensed into the growing medium (Jones,1997).

2.4.1.4 Nutrient uptake

A very critical factor in the production of leafy vegetables is the reduction of nitrate content due to its indirect negative impact on human health. Nitrates are relatively non-toxic; however, their metabolites could be carcinogenic. The taking up of nitrates by plants is affected by many factors such as fertilization practices, soil properties, growing period, air temperature, light intensity and the timing of harvesting. Nicola (2007) reported that nitrate content in rocket leaves grown using the floating systems was 37% less than in the leaves of plants grown using the media based or traditional growing methods. Nitrate availability for plants in soil is hard to control, while the use of hydroponic systems makes it possible to control fertilization, and interrupting fertilization in soilless culture systems before harvesting ensures a reduction of leaf nitrate content in many species.

Plants grown in the gravel and floating systems have 100% of the root area immersed in the nutrient solution, providing a greater opportunity for the plants to assimilate nitrates from the nutrient solution. Wren (1984) also discovered that the NFT system was less efficient in nutrient removal, as compared to the gravel bed culture technique. In the system evaluated, 31% of the nitrates were removed when using gravel beds, and 20% of the nitrates were removed when using the NFT system. Nonetheless, Wren’s (1984) study supports a similar conclusion that gravel hydroponics is more efficient than NFT hydroponics in removing nitrates from fish growing in aquaculture systems. These results showed that, unlike plant nitrate assimilation, plant phosphate assimilation, for instance, was not simply dependent on the root area available to the water column, since the floating system removed less phosphate than the NFT and gravel systems, even though the roots in the floating system were completely immersed in the nutrient solution. Adler et al. (2000) found that plant productivity is determined by the most limiting nutrient(s) present in the nutrient solution and that phosphorous uptake may be increased by supplying those nutrients in shortest supply.

2.4.2 Nutrient Film Technique (NFT)

2.4.2.1 Design characteristics

The NFT was developed in the mid-1960s in England by Dr. Allan Cooper, to overcome the shortcomings of the ebb-and-flow system, such as the difficulty to practice this system on a large scale and the inefficient use of water and nutrients. In this system, the nutrient solution recirculates throughout the entire system by gravitation and enters the growth tray via a water pump without the control by a timer (Domingues et al., 2012; Maboko et al., 2011). The system is slightly sloped so that the nutrient solution is recovered, filtered, replenished and re-circulated into the system. Plants are placed in a channel or a tube with their roots suspended in a hydroponic solution.

2.4.2.2 Growing media types

Growth media can be of organic or inorganic origin. Organic media decomposes at various rates, depending on the specific material. The application and characteristics of organic and inorganic media are therefore different. While there are no optimal substrates for all conditions, some substrates perform better than others in different systems. For example, there are growing media, such as gravel which are used in recirculating systems like the gravel film technique system. While other growing media like perlite or cocopeat are used to fill up net cups where seedlings will be transplanted into different systems depending on the type of hydroponic system being used. Some of the commonly used growing media in the NFT systems are discussed below.

Gravel, rockwool, perlite and sand are classified as inert growing media, which do not have any buffering capacity regarding pH (Niederwieser and Du Plooy, 2014). Inert media are mostly of inorganic origin and are not affected by microbes nor do they sustain microbial growth. The water holding ability of most inert media is approximately 26% of the water absorbing capacity of soil (Jones, 1997). This means that the pores of inert media are much larger than those of soil, with little or no restriction of water leaching out. It is important to adapt the irrigation frequency to ensure that the growth medium does not dry out. Worldwide, rockwool is by far the most common inert medium used because of the wealth of information available from experienced growers and plant scientists. However, with proper management, all of the media mentioned above have a similar yield potential for hydroponically grown crops. Soft aggregates that disintegrate easily should be avoided. These media lose their structure and their particle sizes. This leads to compaction and poor root aeration. As a result of the stability of inert media, they remain effective for many growing seasons provided that water-borne diseases are controlled..

Wood shavings, peat and coir (cocopeat) are organic hydroponic growing media of plant origin and are not chemically inert. This means that the material is able to sustain microbial life, leading to the decomposition of the material. Organic media can be used for one or more growing seasons, depending on the decomposition rate of the material, and the type of crop (Niederwieser and Du Plooy, 2014). An important characteristic of organic media is its isolative capacity, keeping the root temperature relatively constant. Decomposition of media leads to the release of nutrients into the nutrient solution, making various adjustments necessary, e.g. to the pH (Robert, 2003). The grower should choose a supplier who supplies a product that is always available and of high quality (Niederwieser and Du Plooy, 2014).

2.4.2.3 Advantages and disadvantages

There are a number of advantages of the NFT system, which includes the fact that many leafy greens can easily be grown, and commercially the system is most widely used for lettuce production. Some of the plant roots are in the air and some of the roots lies on a moist surface (capillary matting), which provides an adequate supply of water, oxygen and nutrients to the rooting system. The system provides for the ease of plant establishment and the cost of the construction materials is relatively low (Heinen et al., 1991; Ikeda et al., 1995).

The polyethylene film may be either white or black but must be dark enough to keep light out. If light enters the trough, algae growth becomes a challenge. As the root mat increases in size, the nutrient solution flow rate down the hydroline or channel diminishes. Since the roots are constantly immersed in water or nutrient solution, the roots become susceptible to fungal infections. As the nutrient solution flows down the channel, plants at the upper end of the trough reduce the oxygen levels and/or the nutrient concentration in the nutrient solution, a reduction that can be enough to significantly affect the growth and development of plants at the lower end. In addition, as the root mat thickens and becomes denser, the flowing nutrient solution begins to flow over the top and down the outer side of the root mat, decreasing its contact within the root mass (Lennard and Leonard, 2006). The flow interruption results in poor mixing of the current flowing nutrient solution with water and nutrients left behind in the root mat from previous nutrient solution applications. One of the means of minimizing these effects is to make the trough of no longer than 20-25 m in length (Niederwieser and Du Plooy, 2014). Furthermore, the channel can also be made wider, which can accommodate root growth for longer-term crops. If the trough is formed from strips of polyethylene film, it can be discarded after each crop, thus not only increasing the costs, but also necessitating sterilization of the permanent piping and nutrient solution storage tank. Most troughs which are used today are made from different plastic materials, the requirements being dark, structural strength, and ultraviolet (UV) resistance. The design of the trough (width, height, and form) is normally influenced by the type of crop to be planted. Lack of structural strength can lead to unevenness in the trough bottom that allows the nutrient solution to settle in depressions that can lead to anaerobic conditions (Jones, 2016).

2.4.2.4 Nutrient uptake

The NFT systems are suitable to study water and nutrient uptake patterns in plant roots, since they have the smallest buffering, i.e. changes can be observed rapidly, and mixing is almost complete (Graves, 1993; Lennard and Leonard, 2006). Due to the uptake of nutrients by the crop, the levels of nutrients in the plant increases, thus decreasing the nutrient content in the solution (Maboko and Du Plooy, 2012). Lennard and Leonard (2006) found that the NFT system was approximately 20% less efficient in nitrate-nitrogen removal than the deep-water culture and gravel film technique systems. According to Graves (1993) this lower rate of nitrate removal of the NFT system may be due to the fact that the plants in the NFT systems had a root-water contact area of less than 50%, while plants grown in both the ebb-and-flow or GFT and deep-water culture systems had 100% of the root system submerged in the nutrient solution, providing a greater opportunity for the plants to assimilate nitrates from the nutrient solution. Wren (1984) also found that the NFT system was less efficient in terms of nutrient removal than the growing-media based culture systems.

2.4.2.5 Vertical cultivation

There are two different types of recirculating systems in vertical cultivation, depending on their complexity: (1) simple systems that function in less controlled environments like the simple NFT systems (Figure 2.7a) and the bottle garden systems (Figure 2.7b) that can be set up under shade nets or high tunnels, or even under unprotected environments; and (2) complex systems that operate in fully controlled environmental structures.

In recirculating systems or continuous flow solution systems, the nutrient solution constantly flows over the roots whereby a very shallow stream of water containing all of the dissolved nutrients required for plant growth is recirculated over the plant roots in a watertight gully or channel. Ideally, the depth of the closed or recirculating solution should be very shallow (1-3 mm), little more than a thin film of water, hence the name “nutrient film' (Figure 2.7a). This ensures that the thick root mat, which develops in the bottom of the trough, has an upper surface which, although moist, is suspended in the air.

With regards to the recirculating bottle garden system, the nutrient solution is pumped from the tank and delivered to the top layer of the bottles using spaghetti-tubes inserted in each bottle and allowing gravity-driven flow of the solution in each container/bottle below them in the column. The solution flows into the bottom PVC pipe and, subsequently, returns to the tank and is continuously recirculated around the growing systems using a small submersible water pump, capable of delivering above 3100 L·h^{-1}. There is no limit in terms of the height of the system, if the pump is strong enough and light penetration throughout all of the plants is not hampered. An Inert medium like rockwool is perfect for this system and the system is best suited for leafy or shallow rooted crops like Swiss chard/spinach, ALVs, herbs, leafy lettuce, mustard spinach, etc.

With regards to the A-frame system, the spacing between the pipes and the spacing of the holes for the plants are determined by the type of crops to be planted. However, the general recommended spacing between the pipes is 30 cm for leafy crops like Swiss chard/spinach, herbs and leafy lettuce. Strawberry production is also ideal on these systems, using a spacing between pipes of 80-85 cm.

Figure 2.7: Simple recirculating systems with vertical cultivation: (a, https://www.edengreen.com) the nutrient film technique (NFT) operating under a high tunnel; and (b, picture taken by TS Chiloane) the bottle garden system that can be operated in a non-protected environment.

As a result of limited access to land for farming purposes, there is a need for sustainable cropping systems, using less space and natural resources in order to pave the way for adding to food needs (Ahlström et al., 2011). Many aspects press on the food industry and processing, such as population growth and its growing needs accordingly, a reduction of natural resources due to growing cities, soil erosion, different forms of contamination, the advent of biofuels, the impact of climate change on food security, as well as restrictions imposed on food production techniques as affected by consumers and policy providers (Fischetti, 2008). This poses a need for production of higher quality crops, with less use of chemicals (Albajes et al., 2013). Therefore, it has led to an increasing interest in providing healthy food and incorporating these into sustainable development projects (Hui, 2011). The issues raised above can be addressed through vertical farming under fully controlled environmental conditions. Vertical farming has grown as a farming system which combines the design of buildings and farms all together in high-rise hydroponic structures (Kalantari et al., 2017). Vertical farming is a system of growing crops in skyscrapers, to maximize the use of land by having a vertical design (Ahlström et al., 2011; Kalantari et al., 2017), whereby plants are cultivated for food by artificially stacking them vertically above each other (Caplow, 2009; Despommier, 2010; Despommier, 2014; Banerjee et al., 2014; Cicekli et al., 2014). These systems can operate in shipping containers, glasshouse structures, tunnels and abandoned mineshafts (Despommier, 2013; Sivamani et al., 2013). Figure 2.8 illustrates a vertical system for the growing of leafy lettuce, operating under fully controlled environmental conditions in a greenhouse structure.

Figure 2.8: Vertical faming system under a fully controlled greenhouse structure used for growing of leafy lettuce (https://www.edengreen.com).

2.5 suitable food crops for cultivation in active recovery hydroponic systems

2.5.1 Crop types

Crop selection is one of the most critical decisions to make when embarking on active recovery hydroponic systems. This sets the foundation that determines the success or failure of production. Generally, small, relatively fast-growing plants with a short growing period are the most suitable crops for production in active recovery hydroponic systems (Guo et al., 2019; Olfati et al., 2012). However, crop types for production in active recovery systems can be divided into three major groups, namely, leafy, fruiting and herbs according to their usage (Table 2.2).

Leafy vegetables are crops that have leaves that are edible parts of the crop which include Swiss chard, lettuce, kale, etc. (Guo et al., 2019), whereas fruiting crops produce fruits as the edible parts. Herbs have different parts of the plants that can be used, and ranges from the leaves, seeds and fruits (Guo et al., 2019). Out of the three groups, leafy vegetables are the most commonly grown and available in communal gardens (Sharma et al., 2018). Generally, the start-up costs for active recovery hydroponic systems are high when compared to soil-based cultivation systems. Various authors regard this as a considerable drawback for production in active recovery hydroponic systems (Maboko et al., 2012; Sharma et al., 2018). However, the negative impact of this high initial investment cost is reported to be prevalent in low quality markets such as hawkers and street vendors (Alsadon et al., 2013; Guo et al., 2019). In addition, crop productivity (yield and quality) is substantially higher with the implementation of active recovery systems as compared to conventional soil cultivation (Maboko et al., 2011; Souza et al., 2019). Guo et al. (2019) describe leafy vegetables as liability-reducers for farmers, because of the shortened life cycles. For instance, lettuce can be successfully grown in NFT systems, and more than eight harvests per year can be done efficiently in this system.

Fruiting crops for hydroponic systems must produce assimilates for both vegetative and reproductive growth and, as a result, the mineral and water requirements change as the crops grow. Nutrient levels in a system with fruiting crops require more active management than systems with leafy crops. Strawberries are reported as the easiest fruiting crop to grow, due to their small plant structure and low nutrient requirements (De Miranda et al., 2014). Other commonly grown fruiting crops include tomatoes, peppers, squash, and cucumbers, but for commercial purposes these are often grown in active non-recovery hydroponic systems “so-called open bag systems” (Maboko et al., 2012; Pulela et al., 2020). In active recovery hydroponic systems only specific varieties of tomatoes can be grown (for example cherry tomatoes), and these are often cultivated in NFT, ebb-and-flow, and gravel film techniques (GFT) (Maboko et al., 2017; Maboko et al., 2008). However, crops such as tomatoes and peppers require pruning to manage vegetative growth and trellising for mechanical support (Maboko et al., 2011).

Herbs are crops with medicinal properties for human health, and are used as spices for flavour and aroma. These are highly valuable crops and easily grown in active recovery hydroponic systems. The most common herbs for hydroponic production include basil, parsley, coriander and mint (Walters and Currey, 2019). They are generally regarded as multipurpose crops. Parsley, as an example, it is used as a garnish, for flavour and for medicinal purposes (Guo et al., 2019). Their variety of uses give them an advantage over other crop types in the market (Souza et al., 2019).

Table 2.2: Selected high-value crops cultivated in active recovery hydroponic systems obtained from different sources of literature.

Type of crop	Crop	Crop description	Reference
Leafy vegetable	Swish chard (*Beta vulgaris* L.)	A popular crop in hydroponics and greenhouses around the world. The tender leaves grow well in NFT	Maboko and Du Plooy (2013)
	Lettuce (*Lactus sativa* L.)	Generally known as a popular ingredient in salads and sandwiches. Its nutritious leaves are usually eaten raw. It is grown commercially in NFT and ebb-and-flow systems	Fraile-Robayo et al. (2017)
	Kale (*Brassica oleracea* L.)	It is hailed as a superfood due to its nutritional profile. Kale is one of the brassicas family species that is suitable for growth in hydroponics with NFT	Daryada et al. (2019)
Fruiting vegetable	Strawberry (*Fragaria ×ananassa*)	A runner type of crop that can be produced all year round. Many consumers for its flavour prefer it. It is commercially cultivated via NFT and the ebb-and-flow systems	De Miranda et al. (2014)

Table 2.2 ..... Continued

Type of crop	Crop	Crop description	Reference
	Tomato (*Solanum esculantum* L.)	Common crop in hydroponic production worldwide. Due to its tenderness. Trellising is necessary for optimization of fruit yield and quality	Rodriguez-Ortega et al. (2017); Maboko et al. (2013)
	Peppers (*Capsicum annum* L.)	Peppers are common in hydroponics and are mostly grown in the ebb-and-flow system. They need to be pruned and trellised for optimization of fruit yield and quality	Furtado et al. (2017)
Herbs	Basil (*Ocimum basilicum* L.)	It is a natural herb crop that grows well under extended day length conditions. It is becoming a commercial crop commonly grown in NFT systems	Walters and Currey (2019); Olfati et al. (2012)
	Parsley (*Petroselinum crispum* L.)	Mediterranean native crop. Popularly known as a spice and medicinal crop. It is easy to cultivate in NFT systems	Guo et al. (2019)

2.5.2 Factors to consider for crop selection

Choosing suitable crops to grow in hydroponics could be a complex activity because every crop possesses unique morphological characteristics for consideration. However, in this section some important aspects of choosing suitable crops to be cultivated in active recovery hydroponic systems are discussed.

2.5.2.1 Crop morphological characteristics

Crop mass and height: large plants are difficult to support in a confined space and difficult to increase plant density for higher yields. And again, tall plants may experience interspecific competition for light. Maboko et al. (2011) reported that the high foliage of tomato resulted in increased vegetative growth, which affected the fruit size. Hence, to overcome these challenges, growers often trellis and prune plants for better light interception and to limit vegetative growth for enhanced fruit quality. Therefore, it is very important to select plants and crops that are small in size for production in active recovery hydroponic systems. The use of plant-hormone growth regulators is also gaining popularity in hydroponic production to control vegetative growth (Lee et al., 2016).

Size of the root systems: rooting is a necessary process for the plant to absorb mineral elements and water in the nutrient solution (Daryadar et al., 2019). The direction of early root growth is an important consideration for suitability in active recovery hydroponic systems. Tuber and root crops such as potatoes, carrots, and turnips are not suitable for production in these systems, as these have a long growing season and the physiological characteristics of the crops do not benefit from the continuous flow of water, as it is the case in active recovery systems (Maboko and Du Plooy, 2013). Furthermore, highly vigorous and branching rooting crops such as watermelon are discouraged for production in active recovery hydroponics systems. For watermelon, for example, root length increases very rapidly, reaching 20 cm in two weeks after seeding, while the cotyledons are still opening (Guo et al., 2019). Such crops are also not ideal for production in active recovery systems due to the deep and highly branching tap roots which can easily block water circulation, and ultimately water and nutrient uptake by the crop will be limited. Ideally, crops with relatively shallow rooting systems and short plant heights are recommended for production in active recovery systems on a commercial basis. These include tomato, pepper, strawberry and cucumber. Crops with such morphological characteristics often do not perform well in soil as the leaves, stems and fruits can easily be damaged by harsh environmental conditions such as frost and wind, hence, they are suitable for hydroponic cultivation (Pulela et al., 2020; Maboko et al., 2011).

Tenderness: tender crops are often challenging to grow in the active recovery hydroponic systems. This refers to crops that need mechanical support in terms of trellising. Generally, they have herbaceous stems with a high fruit load to support (Maboko and Du Plooy, 2008). Crops that need support include tomatoes, cucumbers, squash, and peppers and these are often growth in open bag hydroponic systems, with the exception of cherry tomatoes. When growing cherry tomatoes in active recovery hydroponic systems, it is very important to consider having poles in the growing structure for trellising, using wire or strings to support the vertical plant growth.

2.5.2.2 Crop environmental requirements

Generally, the crop's environmental requirements are another factor that must be considered when deciding on which crop to grow. This is due to climate variability across different locations and growing seasons, making it an influencing factor on crop production (Kalantari et al., 2017). This is particularly important when using non-environment-controlled systems such as shade nets and high tunnels. Thus, climate requirements for soil-based cultivation may be different from soilless-based cultivation. For instance, precipitation has been the most deciding factor for soil-based crop production, both historically and current. Gomez et al. (2019) reported temperature, light and relative humidity as the most important climatic factors to consider for production in active recovery hydroponics systems. This is because crop production in active recovery systems is mainly done under hydroponic structures such as shade nets and plastic tunnels (Pulela et al., 2020), with recirculating nutrient solutions where water supply is not a limiting factor. Such hydroponic structures are used in an effort to modify production environments in order to maximize crop quality and yield, to extend growing seasons, and to enable crop production under unfavourable environmental conditions, such as strong winds, torrential rainfall, extreme temperatures, and limited solar radiation incidence (Pulela et al., 2020). However, there is a concept called controlled environment agriculture, which is a computerised system that automatically controls temperature and humidity according to the specific requirements of the crop (Gomez et al., 2019). For instance, the optimal temperatures for the production of tomatoes and peppers are 21-25°C during the warm season (Rodriguez-Ortega et al., 2017). Temperature-controlled tunnels will provide and maintain these optimal growing conditions (Gomez et al., 2019). However, some growers are still producing these fruiting crops under shade nets and in high tunnels that are not temperature-controlled because of the large capital investment required for controlled infrastructure. In this regard, it is very important to consider the positioning of the hydroponic structure to ensure sufficient sunlight (Pulela et al., 2020). Although leafy vegetable crops can partially tolerate shade, fruiting crops need sufficient light for the production of optimal fruit size. The principle behind the active recovery hydroponic systems is to recirculate water and nutrients to ensure efficient use of these resources (Guo et al., 2019). Drought suitable plants (for example of rosemary) are not suitable for cultivation in active recovery hydroponic systems (Samadi, 2011). Most vegetables prefer to be hydrated frequently. Aeration is important for their large root masses and a porous substrate can better provide oxygen to the roots than floating passive hydroponic systems like the deep-water culture (DWC) system. This is important because oxygen facilitates respiration for root growth, and porous growing media ensures good aeration (Samadi, 2011).

2.5.2.3 Economic value of the crops

Crop production decisions should consider the market value of the crop and consumer demand (Gilmour et al., 2019). It is a very common principle in economics that if the demand for the product is low, the crop will not do well in the market. Therefore, production of these crops may be unwise. Crop production should focus on high value crops and crops that are in high demand. From this point of view, Souza et al. (2019) evaluated the economic viability of a hydroponic system using a distinguished approach to determine investment risk. The results revealed that crops such as parsley, kale and strawberry are highly valuable in the market, whereas tomatoes and peppers are always in demand. According to Souza et al. (2019) herbs are the most valuable crops, followed by fruiting and leafy vegetables. Herbs are high-value crops with a continuous yield (Guo et al., 2019). Crops such as kale and sweet basil are examples of crops that can be cultivated continuously for an extended period (Yang and Kim, 2020; Gilmour et al., 2019). However, it is also important to consider crops that are very popular in the communities and that are constantly in demand (Walters and Currey, 2019). These crops include Swiss chard, kale and tomatoes. Due to their high demand in the market, these crops have the potential for high economic returns on investment (Yang and Kim, 2020).

2.6 Hydroponic structures for operation of active recovery systems

Prospective hydroponic farmers are often confronted with the need to decide on the type and size of the systems to adopt. Farmers that are already into production also sometimes ponder on whether the systems that they are using are the best for their environments. A literature study was performed to evaluate the popularity of non-controlled and controlled hydroponic structures for the operation of active recovery hydroponic systems worldwide. Dimensions of the structures and environmental characteristics of the experimental locations formed the collected dataset. It is important to point out that the categorization used in the current study was only meant to facilitate the intended analyses. For example, latitudes and altitudes were categorized into latitudinal climate and altitude zones, respectively as defined in (Table 2.3)

Table 2.3: Definitions of latitudinal climate and altitude zones.

Factor class	Factor class	Definition
Latitudinal climate	Tropic	<23.5° north and south of the equator
	Temperate	23.5-66.5° north and south of the equator
	Arctic	>66.5° north and south of the equator
Altitude	Low altitude	<100 m.a.s.l
	Mid altitude	100-1000 m.a.s.l
	High altitude	>1000 m.a.s.l

m.a.s.l – Metres above sea level

The quality of the available water and the type of crops cultivated were also used as factors in the analysis in the current study. When the information was not provided, it was assumed that water of domestic water quality was used. The results of the analyses are elaborated on in the following sections.

2.6.1 Non-controlled systems

Non-controlled hydroponic structures are systems constructed in such a way that the microclimate inside the structure is similar to the ambient environment climatic conditions because heat and gaseous exchanges are not restricted. (Table 2.4) below is a summarised version of the dataset created from papers that reported on non-controlled hydroponic structures for active recovery systems worldwide.

Table 2.4: Sources and site locations of the experiments that provided information on non-controlled hydroponic structures used in the current analysis.

No.	Country	LONG (°)	LAT (°)	Latitudinal Climate	Altitude (m.a.s.l)	Altitude class	Reference
1	Australia	151.33	-33.37	Temperat e	197	Mid	Sarooshi and Cresswell, (1994)
2	Brazil	-40.87	-3.97	Tropic	920	Mid	Almeida et al. (2019)
3	Brazil	-39.11	-12.67	Tropic	220	Mid	Dos Santos et al. (2019)
4	Colombia	-73.38	5,53	Tropic	2690	High	Fraile-Robayo et al. (2017)
5	Malaysia	101.72	3.00	Tropic	51	Low	Mia et al. (2010)
6	RSA	28.58	-25.98	Temperat e	1200	High	Mampholo et al. (2018)
7	RSA	28.58	-25.98	Temperat e	1200	High	Mahlangu et al. (2016)
8	RSA	28.58	-25.98	Temperat e	1200	High	Maboko and Du Plooy (2013)
9	RSA	28.58	-25.98	Temperat e	1200	High	Maboko and Du Plooy (2018)
10	RSA	19.31	-33.36	Temperat e	462	Mid	Maatjie et al. (2018)
11	Vietnam	105.75	10,02	Tropic	2	Low	Diem et al. (2017)

The results from this table suggest that non-controlled structures are more popular in the southern hemisphere than in the northern hemisphere. South Africa contributed most of the sites from the southern hemisphere. The results also suggest that the non-controlled structures are equally popular in the tropical and temperate climates, which are important zones for agricultural production. There was a noticeable absence of these types of structures in the arctic region. With respect to altitude, the structures were more prevalent in the mid and high altitude zones than in the low altitude regions.

The non-controlled hydroponic structures for active recovery systems can further be categorised into shade nets and high tunnels. However, one paper (Diem et al., 1027) reported on a hydroponic system practised in the open. The following sections present the analysis of the results for the two non-controlled system classes.

2.6.1.1 Shade nets

Shade nets are structures where nets are used as the roofs and walls. Although a special microclimate might be created inside the shade net, the exchange of gases between the inside and outside of the structure is not restricted. Heat exchange is also fast, hence, the climate on the inside tends to change rapidly as the climate changes on the outside. Their main purpose is to reduce direct solar radiation onto the crops under production. However, other multiple benefits come with the use of shade nets, such as keeping out of macro pests. All the shade hydroponic systems indicated in (Table 2.5) used water of domestic quality.

Table 2.5: Sources and data provided on shade net-based systems used in the current analysis.

No.	L (m)	W (m)	H (m)	Crops	Reference
1	-	-	-	Lettuce (*Lactuca sativa* L.)	Mampholo et al. (2018)
2	1.30	0.70	0.20	Lettuce (*Lactuca sativa* L.)	Mahlangu et al. (2016)
3	-	-	-	Lettuce (*Lactuca sativa* L.)	Fraile-Robayo et al. (2017)
4	-	-	-	Swiss chard cultivars (*Beta vulgaris* L.)	Maboko and Du Plooy (2013)
5	-	-	-	Mustard spinach (*Brassica juncea* L.); Chinese cabbage (*B. rapa* L.)	Maboko and Du Plooy (2018)
6	-	-	-	Mustard spinach (*Brassica juncea* L.); Chinese cabbage (*B. rapa* L.)	Maboko and Du Plooy (2018)
7	-	-	-	Strawberry (*Fragaria ananassa*)	Sarooshi and Cresswell (1994)

*Notes: L, W and H are the reported length, width and height of the structures, respectively
– data not shown

Based on the above results, seven of the 11 non-controlled hydroponic systems were shade nets (Table 2.5). The results indicate that leafy vegetables were the most popular crop type produced in the non-controlled hydroponic shade nets. Lettuce dominated this group of crop types. However, there was a report of bananas produced in a shade net in Malaysia (Mia et al., 2010). The results also showed that authors had no appetite to report on dimensional properties (length, width and height) of the structures they used. Only one paper from South Africa (Mahlangu et al., 2016) recorded some dimensions, which were probably the dimensional properties of the planting trays (seed beds) used. It was not clear if the South African system was for experimental or commercial purposes.

2.6.1.2 Non-temperature controlled tunnels

Unlike shade nets, non-temperature controlled tunnels are hydroponic structures that are constructed from non-porous materials. However, there are large, designated areas in the structures that can be opened or closed to ensure that gaseous and heat exchanges between the inside of the structure and the outside environment are not restricted. These structures are also used to limit direct solar radiation onto the crops. In some environments, these structures are used to protect the crops against hailstorms and to keep out large animals that might damage the crops. The results from the current analysis are presented in (Table 2.6).

Table 2.6: Sources and data provided on non-temperature-controlled tunnels-based systems used in the current analysis.

No.	L (m)	W (m)	H (m)	Crops	Reference
1	24.00	2.00	0.80	Strawberry	Almeida et al. (2019)
2	33.00	7.00	-	Basil	Dos Santos et al. (2019)
3	-	-	-	Tomato (*Solanum lycopersicum* L.)	Maatjie et al. (2018)

*Notes: L, W and H are the reported length, width and height of the structure, respectively
– data not shown

Results presented in Table 2.6 indicate that non-temperature-controlled tunnels can be used to produce fruity vegetables, such as strawberries and tomatoes, and for the production of leafy crops like herbs. Countries in the southern hemisphere using this technology included Brazil (Almeida et al., 2019; Dos Santos et al., 2019) and South Africa (Maatjie et al., 2018). Most of the systems used domestic water (Almeida et al., 2019; Maatjie et al., 2018), but Dos Santos et al. (2019) used saline water. The results also suggest that Brazilian users of this technology had deemed it important to report on the dimensional properties of their structures. The high tunnels averaged 28.5 m in length and 4.5 m in width. Nevertheless, only one paper (Almeida et al., 2019) provided information on the height of the structure, which was 0.80 m.

2.6.2 Controlled systems

Controlled hydroponic production systems for active recovery are constructed and equipped in such a way that the ambient microclimate inside the structure is controlled to exhibit the desired climatic conditions. Therefore, the microclimates within these structures differ from the outside naturally occurring climatic conditions. The control is effected by restricting the exchange of gases and heat between the inside of the structure and the external environment.

(Table 2.7) presents a summarised version of the dataset compiled from papers that reported on controlled hydroponic structures for active recover systems from across the world. The results presented in this table suggest that, unlike the non-controlled hydroponic structures, the controlled hydroponic structures are far more popular in the northern hemisphere than the southern hemisphere (60 in the northern hemisphere vs. seven in the southern hemisphere).

The United States (US) (17) contributed most of the data points from North America, and Italy (13) contributed most of the data points from Europe, while South Korea (SK) provided the largest contribution (5) from Asia. Kenya represented Africa with a single contribution to the dataset. The results also suggest that the controlled structures are far more popular in the temperate climates (61) than in both the tropical (5) and arctic (1) climates. As already alluded to, the temperate zone is the region in which most of the agricultural production takes place. The results also indicate a high popularity of the structures in the low (32) and mid (29) altitude zones, which are important for agriculture, especially horticulture. The high-altitude zones had far less data points (6) in comparison to these two zones.

For the purposes of the current study analyses, the controlled hydroponic structures for active recovery systems were further grouped into semi-controlled temperature structures and fully-controlled environment structures or greenhouses. Sections 2.5.2.1 and 2.5.2.2 present the analysis of the results for the two controlled system classes, respectively.

2.6.2.1 Semi-controlled temperature structures

Semi-controlled greenhouses are generally constructed from transparent materials such as plastic and glass, with automated regulation of few climatic factors. They let in solar radiation from outside, but the structures trap most of the heat that enters inside in order to create a microclimate that is significantly different from the outside ambient climate. No heating nor lighting facilities are normally installed inside the structure. However, ventilation doors are installed on the structure walls and/or roof. Regulation of air movement through these doors regulate the inside microclimate. The data from semi-controlled hydroponic systems used in the current analysis are presented in Tables 2.7 and 2.8.

Table 2.7: Sources and site locations of the experiments that provided information on semi-controlled systems used in the current analysis.

No	Reference	Country	LONG (°)	LAT (°)	Latitudinal Climate	Altitude (m.a.s.l)	Altitude class
1	Lennard and Leonard (2006)	Australia	144.97	-36.18	Temperate	48	Low
2	Chekli et al. (2017)	Australia	151.22	-33.87	Temperate	22	Low
3	Tikasz et al. (2019)	Canada	-73.93	45.40	Temperate	25	Low
4	Alcarraz et al. (2018)	Chile	-70.67	-33.67	Temperate	546	Mid
5	Li et al. (2019)	China	121.45	31.03	Temperate	18	Low
6	Yan et al. (2019)	China	116.35	40.00	Temperate	50	Low
7	Babmann et al. (2017)	Germany	12.12	54.07	Temperate	33	Low
8	Claussen (2002)	Germany	13.32	52.35	Temperate	40	Low
9	Suhl et al. (2016)	Germany	13.40	52.52	Temperate	24	Low
10	Lykas et al. (2006)	Greece	23.32	83.00	Arctic	85	Low
11	Kotsiras et al. (2016)	Greece	22.11	37.04	Temperate	20	Low
12	Ntinas et al. (2019)	Greece	23.00	40.54	Temperate	-1	Low
13	Kaur et al. (2018)	India	75.87	30.93	Temperate	249	Mid
14	Frasetya et al. (2019)	Indonesia	107.78	-6.93	Tropic	744	Mid

No	Reference	Country	LONG (°)	LAT (°)	Latitudinal Climate	Altitude (m.a.s.l)	Altitude class
15	Hooshmand et al. (2019)	Iran	48.67	31.32	Temperate	18	Low
16	Roosta (2014)	Iran	55.93	30.39	Temperate	1523	High
17	Nicola et al. (2005)	Italy	8.08	45.37	Temperate	303	Mid
18	D'Imperio et al. (2016)	Italy	17.07	41.05	Temperate	24	Low
19	Gonnella et al. (2003)	Italy	17.07	41.05	Temperate	24	Low
20	Fallovo et al. (2009)	Italy	12.13	42.42	Temperate	310	Mid
21	D'Imperio et al. (2015)	Italy	17.07	41,05	Temperate	24	Low
22	Giordano et al. (2019)	Italy	14.27	40,85	Temperate	33	Low
23	Moncada et al. (2018)	Italy	13.33	38.16	Temperate	48	Low
24	Miceli et al. (2019)	Italy	13.35	38.11	Temperate	49	Low
25	Manzocco et al. (2010)	Italy	13.22	46.08	Temperate	117	Mid
26	Ronga et al. (2019)	Italy	10.93	44.65	Temperate	49	Low
27	Orsini et al. (2018)	Italy	11.41	44.55	Temperate	25	Low
28	Barone et al. (2018)	Italy	15.07	37.53	Temperate	186	Mid
29	Pantanella et al. (2012)	Italy	12.13	42.42	Temperate	310	Mid a
30	Sakamoto et al. (2020)	Japan	135.58	34.65	Temperate	3	Low
31	Tamaki et al. (2020)	Japan	139,77	35.70	Temperate	11	Low
32	Gichana et al. (2019)	Kenya	37.28	-1.50	Tropic	2000	High
33	Albaho et al. (2008)	Kuwait	47.90	29.35	Temperate	10	Low
34	Silva et al. (2015)	Mexico	-89.63	21.02	Tropic	11	Low
35	Alvarado-Camarillo et al. (2020)	Mexico	-101.05	25.50	Temperate	1610	High
36	Ramírez-Gómez et al. (2012)	Mexico	-98.90	19.47	Tropic	2244	High
37	Lennard and Ward (2019)	NZ	172.95	-41.07	Temperate	303	Mid
38	Strzemski et al. (2019)	Poland	22.55	51.5	Temperate	193	Mid
39	Sochacki and Milosz (2019)	Poland	20.85	52.20	Temperate	110	Mid
40	Cho et al. (2017)	SK	126.95	37.47	Temperate	95	Low
41	Jung et al. (2015)	SK	126.95	37.47	Temperate	95	Low
42	Lee et al. (2017)	SK	128.85	37.80	Temperate	54	Low
43	Park et al. (2020)	SK	127.45	36.63	Temperate	60	Low
44	Lee et al. (2019)	SK	127.12	36.17	Temperate	10	Low
45	Ritter et al. (2001)	Spain	-2.60	42.83	Temperate	521	Mid
46	Antolinos et al. (2020)	Spain	-2.28	36.85	Temperate	90	Low
47	Schmautz et al. (2016)	Switzerland	8.68	-47.22	Temperate	509	Mid
48	Nozzi et al. (2018)	Switzerland	47.22	8.68	Tropic	509	Mid
49	Incemehmetoglu (2012)	Turkey	32.93	39.88	Temperate	1079	High
50	Leibar-Porcel et al. (2020)	UK	-2.78	54.02	Temperate	60	Low
51	Heredia (2014)	US	-120.67	35.30	Temperate	109	Mid
52	Wortman (2015)	US	-88.22	40.10	Temperate	230	Mid
53	Sapkota et al. (2019)	US	-103.35	34.18	Temperate	1221	High
54	Christie (2014)	US	-81.78	32.43	Temperate	74	Low
55	Hernandez et al. (2020)	US	-76.47	42.45	Temperate	279	Mid
56	Schwartz et al. (2019)	US	-76.47	42.45	Temperate	279	Mid
57	Wielgosz et al. (2017)	US	-76.00	42.00	Temperate	281	Mid
58	Niu et al. (2018)	US	-96.35	30.60	Temperate	122	Mid
59	Li et al. (2018)	US	-96.33	30.62	Temperate	105	Mid
60	Vandam et al. (2017)	US	-76.48	42.45	Temperate	252	Mid
61	Anderson et al. (2017)	US	-76.48	42.45	Temperate	252	Mid
62	Janeczko and Timmons (2019)	US	-76.48	42.45	Temperate	248	Mid
63	Yang and Kim (2020a)	US	-86.00	40.00	Temperate	190	Mid
64	Sublett et al. (2018)	US	-89.00	34.00	Temperate	123	Mid
65	Blanchard et al. (2020)	US	-85.48	32.60	Temperate	225	Mid
66	Singh et al. (2020)	US	-97.07	36.02	Temperate	280	Mid
67	Yang and Kim (2020b)	US	-86.00	40.00	Temperate	190	Mid

Table 2.8: Sources and data provided on semi-controlled hydroponic systems used in the current analysis.

No.	Reference	L (m)	W (m)	H (m)	Water quality	Crops
1	Lennard and Leonard (2006)	0.78	0.67	0.22	D	Lettuce (*Lactuca sativa* L.); Murray Cod (*Maccullochella peelii peelii*)
2	Tikasz et al. (2019)	-	-	-	P	Lettuce (Lactuca sativa L.); Kale (*Brassica napusvar*)
3	Alcarraz et al. (2018)				D	Lettuce (*Lactuca sativa* L.); Rainbow trout (*Oncorhynchus mykiss*)
4	Li et al. (2019)	-	-	-	D	Celery (*Oenanthe javanica*); Spinach (*Myriophyllum Spicatum*); Tilapia (*Oreochromis mossambicus*); Crucian (*Carasssius auratus*)
5	Claussen (2002)	-	-	-	D	Tomato (*Lycopersicon esculentum*)
6	Babmann et al. (2017)	-	-	-	D	Cucumbers (*Cucumis sativus*); Clarias (*Gariepinus Burchell*)
7	Lykas et al. (2006)	-	-	-	D	Rose *(Rosa hybrida)*
8	Kotsiras et al. (2016)	10.00	4.00	0.30	D	Lettuce (*Lactuca sativa* L.)
9	Ntinas et al. (2019)	-	-	-	D	Tomato (*Solanum lycopersicum* L.)
10	Frasetya et al. (2019)	-	-	-	D	Lettuce (*Lactuca sativa L.*)
11	Miceli et al. (2019)	-	-	-	D	Lettuce (*Lactuca sativa L.*); Rocket (*Eruca sativa* L.)
12	Moncada et al. (2018)	-	-	-	D	Lettuce (*Lactuca sativa* L.), Escarole (*Cichorium endivia* L.), Curly endive (*Cichorium endivia* L.)
13	D'Imperio et al. (2016)	-	-	-	D	Basil (*Ocimum basilicum* L.); mizuna (*Brassica rapa* L.); Tatsoi (*Brassica rapa* L.); endive
14	Gonnella et al. (2003)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
15	D'Imperio et al. (2015)	-	-	-	D	Tatsoi (*Brassica rapa L.*); Mizuna (*Brassica rapa* L.); Purslane (*Portulaca oleracea* L.); Basil (*Ocimum basilicum L.*); Swiss chard (*Beta vulgaris* L.); Chicory (*Cichorium intybus* L.)
16	Orsini et al. (2018)	-	-	-	D	Lettuce (*Lactuca sativa* L)
17	Pantanella et al. (2012)	-	-	-	D	Lettuce (*Lactuca sativa* L.); Nile tilapia (*Oreochromis niloticus* L.)
18	Sakamoto et al. (2020)	-	-	-	D	Carrots (*Daucus carota* L.)
19	Gichana et al. (2019)	-	-	-	D	Artemisia annua; Oreochromis niloticus
20	Alvarado-Camarillo et al. (2020)	-	-	-	D	Lettuce (*Lactuca sativavar* L.)
21	Ramírez-Gómez et al. (2012)	-	-	-	D	Strawberry (*Fragaria ananassa Duch.*)
22	Silva et al. (2015)	-	-	-	D	Pak choy (*Brassica chinensis*); Coriander (*Coriandrum sativum*); Nile tilapia (*Oreochromis niloticus*)
23	Sochacki and Milosz (2019)	-	-	-	D	Tulips
24	Lee et al. (2019)	-	-	-	D	Tomato (*Solanum lycopersicum* L.*)*
25	Park et al. (2020)	-	-	-	D	Houtt (*Crepidiastrum denticulatum*); Pak choi (*Brassica rapa*); Kawano
26	Antolinos et al. (2020)	-	-	-	P	Tomato (*Solanum lycopersicum* L.)
27	Leibar-Porcel et al. (2020)	-	-	-	D	Lettuce (*Lactuca sativa* L.); Pepper (*Capsicum annuum* L.)
28	Sapkota et al. (2019)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
29	Christie (2014)	4.57	3.66	-	P	Lettuce (*Lactuca sativa* L.)
30	Niu et al. (2018)	-	-	-	P & D	Lettuce (*Lactuca sativa* L.); Pak choi (*Brassica rapa*)
31	Li et al. (2018)	24.00	12.80	-	D	Lettuce (*Lactuca sativa* L.)
32	Blanchard et al. (2020)	29.30	9.10	-	D	Cucumber (*Cucumis sativus* L.); Tilapia (*Oreochromis niloticus*)
33	Hernandez et al. (2020)	-	-	-	D	Lettuce (*Lactuca sativa L.*)
34	Schwartz et al. (2019)	9.10	1.30	0.91	D	Lettuce (*Lactuca sativa* L.); Koi (*Cyprinus carpio*)

*Notes: L, W and H are recorded length, width and height of the structure, respectively; water quality: D = domestic, P=purified

– data not shown

The results in (Table 2.8) suggst that semi-controlled greenhouses are a popular technology because they contributed 34 data points of the dataset. Majority of the hydroponic systems used domestic water quality, while only three used purified water quality (Antolinos et al., 2020; Tikasz et al., 2019; Christie, 2014) and one used a combination of domestic and purified water quality (Niu et al., 2018). Leafy vegetables were the most dominant crop produced under the semi-controlled hydroponic systems. Lettuce also dominated the leafy vegetables produced by appearing in 18 of the 34 reports. Of particular note was the inclusion of fish in some of the systems (Blanchard et al., 2020; Silva et al., 2015; Pantanella et al., 2012). The results also showed a general lack of appetite on report on the dimensional properties of the structures used. The results of the dimensional properties in the table suggest possible inconsistencies or lack of clarity on the structures to report on. For instance, it was difficult to imagine a hydroponic structure in the current sense that is as small as 0.78 m in length and 0.67 m in width (Lennard and Leonard, 2006) or 0.22-0.30 m in height (Kotsiras et al., 2016; Lennard and Leonard, 2006). This further exposes the challenges of lacking universally scientific reporting systems. In the current case, some authors might have reported on dimensional properties of housing structures, while others probably reported on dimensions of planting trays. Such inconsistencies often hinder comparisons across sites.

2.6.2.2 Greenhouses

Unlike semi-controlled systems, fully controlled greenhouses are actually insulated against the outside environment. In-house temperature is regulated by thermostat-controlled heating systems. Light intensity is regulated by special lamps, which emit specially controlled light intensities to suit the requirements. Ventilation is provided artificially by means of fans and air vents. This way, the in-house microclimate can precisely be controlled. These systems are quite expensive to construct and run; hence, they are mostly used for experiments or very high valued crops. The results in Table 2.9 suggest that the fully controlled systems are also popular technology with a contribution of 33 data points to the dataset in (Table 2.9) Water of domestic quality was used in the majority of the systems, while only two used purified water quality (Yang and Kim, 2020b; Fallovo et al., 2009). Once again, lettuce dominated the leafy vegetables produced in the system. In fact, leafy vegetables were the dominant crop produced under the fully-controlled greenhouses. The inclusion of fish was also noticed in two of the systems (Nozzi et al., 2018; Suhl et al., 2016).

Table 2.9: Sources and data provided on fully controlled greenhouses based systems used in the current analysis.

No.	Reference	L (m)	W (m)	H (m)	Water quality	Crops
1	Roosta (2014)	-	-	-	D	Basil (*Ocimum basilicum* L.); Common carp (*Cyprinus carpio*); Grass carp (*Ctenopharyngodon idella*); Silver carp (*Hypophthalmichthys molitrix*)
2	Incemehmetoglu (2012)	-	-	-	D	Strawberries (*Fragaria versca* L.)
3	Chekli et al. (2017)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
4	Albaho et al. (2008)	-	-	-	D	Pepper (*Capsicum annuum* L); Strawberries (*Fragaria versca* L.)
5	Hooshmand et al. (2019)	-	-	-	D	Tomato (*Solanum lycopersicum* L.)
6	Tamaki et al. (2020)				D	Komatsuna (*Brassica rapa*); Spinach (*Spinacia oleracea* L.)
7	Cho et al. (2017)	3.00	2.40	2,20	D	Lettuce (*Lactuca sativa* L.)
8	Jung et al. (2015)	3.00	2.40	2.20	D	Lettuce (Lactuca sativa L.)
9	Lee et al. (2017)	-	-	-	D	Tomato (*Solanum lycopersicum* L.)
10	Yan et al. (2019)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
11	Giordano et al. (2019)	7.00	4.00	2.10	D	Lettuce (*Lactuca sativa* L.)
12	Ronga et al. (2019)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
13	Schmautz et al. (2016)	-	-	-	D	Tomato (*Solanum lycopersicum* L.); Nile tilapia (*Oreochromis niloticus*)
14	Lennard and Ward (2019)	18.00	9.00	4.00	D	Lettuce (*Lactuca sativa* L.); Dill (*Anethum graveolens* L.); Rocket (*Eruca sativa*), Coriander (*Coriandrum sativum* L.); Parsley (*Petroselinum crispum*); Grass Carp (*Ctenopharyngodon idella*)
15	Kaur et al. (2018)	-	-	-	D	Tomato (*Solanum lycopersicum* L.)
16	Sublett et al. (2018)	-	-	-	D	Lettuce (*Lactuca sativa* L.)
17	Heredia. (2014)	1.83	1.83	1.17	D	Lettuce (*Lactuca sativa* L.); Spinach; Swiss Chard (*Beta vulgaris* L.); Kale
18	Singh et al. (2020)	-	-	-	D	Lettuce (*Lactuca sativa* L.); Basil (*Ocimum basilicum L.*); Swiss chard (*Beta vulgaris* L.)
19	Barone et al. (2018)	-	-	-	D	Tomato (*Solanum lycopersicum* L.)
20	Yang and Kim (2020a)	-	-	-	D	Lettuce (*Lactuca sativa* L.); Chinese cabbage (*Brassica rapa*); Mustard (*Brassica juncea*); Chia (*Salvia hispanica*); Basil (*Ocimum basilicum*); Swiss chard (*Beta vulgaris*)
21	Yang and Kim (2020b)	-	-	-	P	Lettuce (*Lactuca sativa* L.); Tomato (Lycopersicon esculentum); Basil (*Ocimum basilicum*); Nile tilapia (*Oreochromis niloticus* L.)
22	Wortman (2015)	-	-	-	D	Basil (Ocimum basilicum L.), kale (*Brassica oleracea* L.), chipotle pepper (*Capsicum annuum L.*); Tomato (*Solanum lycopersicum L.*)
23	Wielgosz et al. (2017)	10.00	9.00	7.00		Lettuce (*Lactuca sativa* L.); Koi (*Cyprinus carpio*)
24	Fallovo et al. (2009)	-	-	-	P	Lettuce (*Lactuca sativa* L.)
25	Vandam et al. (2017)	11.00	9.00	7.00	D	Spinach (*Spinacia oleracea*); Koi (*Cyprinus carpio*)
26	Anderson et al. (2017)	10.00	7.00	7.00	D	Lettuce (*Lactuca sativa* L.)
27	Janeczko and Timmons (2019)	11.00	9.00	7.00	D	Spinach (*Spinacia oleracea*)
28	Ritter et al. (2001)	-	-	-	D	Potato (*Solanum tuberosum* L.)
29	Nicola et al., 2005	-	-	-	D	Rocket (*Eruca sativa*)
30	Manzocco et al. (2010)	-	-	-	D	Corn salad (*Valerianella locusta* L.)
31	Strzemski et al. (2019)	-	-	-	D	C. acaulis
32	Nozzi et al. (2018)	-	-	-	D	Lettuce (*Lactuca sativa* L.); Mint (*Mentha piperita*); Mushroom (*Rungia klossii*); Nile tilapia (*Oreochromis niloticus*)
33	Suhl et al. (2016)	-	-	4.20	D	Tomatoes (*Solanum lycopersicum* L.); Tilapia (*Oreochromis niloticus*)

*Notes: L, W and H are recorded length, width and height of the structure, respectively; water quality: D = domestic, P=purified – data not shown

The reporting on the dimensional properties of the fully controlled greenhouse systems used was better than that reported for the semi-controlled systems. The average length of the fully controlled greenhouses was 8.31 m, while the average width was 5.96 m and the average height was 4.39 m.

2.7 Management of active recovery hydroponic systems

Active recovery hydroponic systems generally operate in protected hydroponic structures to minimize the effects of extreme weather conditions on plant growth and to minimize maintenance of the systems. Water is continuously recaptured and recirculated to the crops using an irrigation pump. Thus, there are several important factors that need to be considered to ensure adequate management of these systems, including fertigation scheduling, management of the nutrient solution, water flow rates, monitoring of the environmental conditions, the quality of the water supply and management of nutrient deficiencies due to abiotic and biotic factors. This section will elaborate on how to manage these factors for increased efficiency in the performance of these systems as well as increased crop productivity.

2.7.1 Fertigation and management of nutrient solution

In active recovery hydroponic systems, the crops are fertigated through a combination of fertilization and irrigation, by means of a recirculating nutrient solution. For this purpose, water-soluble fertilizers are added to the irrigation system. Water-soluble fertilizers are multi-compound fertilizers that can be dissolved in water, enabling them to be more easily absorbed by the plants. The nutrient solution must contain a full range of both macro and micronutrients that are important for crop growth and development, since hydroponic systems operate under soilless culture conditions (Dunn, 2013). In addition, crops also require carbon, hydrogen and oxygen, which should be made available in the air and water that are in contact with the plants. Table 2.10 indicates the ionic forms of the macro and micronutrients, as well as the normal concentration range of these found in most nutrient solutions of hydroponic systems. These nutrients comprise of nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, copper, iron, manganese, molybdenum and zinc. Calcium is available to crops through calcium nitrate ($CaNO_3$), while other multi-compound fertilizers such as Hygroponics or Multifeed soluble fertilizers supply the remaining nutrients. Micronutrients are seldom deficient in crops, with the exception of iron that can easily be supplemented in the nutrient solution using amino acid iron chelates (Lester, 2014). This is because iron is needed in crops for several functions, including chlorophyll production, as an oxygen carrier, and for chemical reactions involved in cell division and growth.

Table 2.10: The ionic forms of the macro and micronutrients, as well as the normal concentration range of these found in most nutrient solutions of hydroponic systems (Jones, 2005).

Nutrient	Ionic form	Concentration range (mg/L)
Macronutrients		
Nitrogen (N)	NO_3^-, NH_4^+	100 to 200
Phosphorus (P)	HPO_4^{2-},$H_2PO_4^-$	15 to 30
Potassium (K)	K^+	100 to 200
Calcium (Ca)	Ca^{2+}	200 to 300
Magnesium (Mg)	Mg^{2+}	30 to 80
Sulfur (S)	SO_4^{2-}	70 to 150
Micronutrients		
Boron (B)	BO_3^{3-}	0.03
Copper (Cu)	Cu^{2+}	0.01 to 0.10
Iron (Fe)	Fe^{2+}, Fe^{3+}	2.00 to 12.00
Manganese (Mn)	Mn^{2+}	0.50 to 2.00
Molybdenum (Mo)	$Mo0_4^-$	0.05
Zinc (Zn)	Zn^{2+}	0.05 to 0.5

In active recovery hydroponic systems, the nutrient solution is often managed through frequent monitoring of the electrical conductivity (EC) and pH to ensure that these are maintained at the optimal levels for crop growth and development (Maboko and Du Plooy, 2013; De Miranda et al., 2014; Fraile-robayo et al., 2017). This is because the drained nutrient solution after circulation through the plant roots is reused in the system, which often leads to deficit and/or an accumulation of nutrients and other ions in the solution, resulting in a changing nutrient ratio (Schröder and Lieth, 2002). Thus, since nutrients are added to the water tanks through the addition of multi-compound fertilizers, such as Hygroponics, it becomes difficult to know the concentration of each nutrient individually in the solution during the recirculation. The nutrient solution in the tank is thus often replaced periodically (on a weekly basis) to maintain the necessary levels of nutrients required for optimal crop production. This also prevents the detrimental build-up of unused ions. However, this method of nutrient management can contribute to environmental pollution to some extent.

Dunn (2013) describes four other techniques that are utilized for nutrient management in active recovery hydroponic systems, with some options being more complex and costly than others. The first technique involves the automated control of the added water and nutrients into the tank to maintain the desired levels of pH and EC. The pH of the nutrient solution is automatically adjusted to the ideal level for hydroponic production, which is between 5.0 and 6.0, while the EC level is kept within the range of 1.5 to 3.0 dS m^{-1}, depending on the type of crop (Sharma et al., 2018). This is the ideal method of nutrient solution management, but it is expensive and, as a result, its utilization is only viable for large-scale commercial production. In the second technique, only the water level is maintained at a steady level automatically, by means of a floating valve. In this system, both water and nutrients are utilized, but only the water is constantly replaced to maintain the desired level in the tank. Thus, it is necessary to check the EC and pH of the nutrient solution periodically, and these must be adjusted if required by manually adding nutrients, or by adding an acid (sulfuric or nitric acid) if the pH of the solution needs to be lowered, or by adding an alkali (sodium hydroxide) if the pH of the solution needs to be raised to the desired level. This method is more affordable, but less accurate, since it is not possible to determine the exact concentration of each of the different nutrients present in the solution, thus not allowing for the individual correction of the concentration of each of the nutrients in the solution (Cho et al., 2017). The third and fourth techniques are both manual and much more affordable but have the same limitations as the previous method. In both cases, the holding tank is partly or almost completely emptied, before it is refilled by adding water and nutrients. The difference between the two techniques is that, in the one technique the nutrient solution is checked during refilling to ensure that the correct EC and pH levels are maintained, while in the other technique, a standard strength nutrient solution is added without determining the resultant EC and pH of the solution. These last two techniques may offer a practical alternative to nutrient management, but in active recovery hydroponic systems, this is likely to result in nutrient imbalances, since the solution is continuously recirculated through the plant roots, resulting in changes in the concentrations of the nutrients in the solution. Thus, it is suggested that the EC and pH of the solution be checked and adjusted periodically to maintain adequate levels of nutrients for optimal plant growth. However, this method may result in the build-up of elements like calcium, magnesium and sulfate over time. Thus, replacing of the nutrient solution occasionally is recommended (Bugbee, 2004). To date, there are no studies that have determined the EC threshold levels as an indication of when the nutrient solution should be replaced. This information is needed for active recovery systems, since the frequency of refilling of the nutrient solution is determined by the ratio of the concentration of nutrients in the solution to plant growth rate (Bugbee, 2004). In addition, the tolerance of a nutrient imbalance in the solution may be a crop-specific trait, as some crops have a higher ability than others to store the nutrients that were rapidly absorbed from the solution in the roots, stems or leaves, and to remobilize them as needed.

2.7.2 Detection and management of nutrient deficiencies

In active recovery systems, it is crucial to detect nutrient deficiencies in the solution before these deficiencies cause nutrient deficiencies within the plant. In fully automated systems, deficiencies in the nutrient solution practically do not occur, since there is an automated replenishment of fertilizers and water in the proper ratios based on the real-time measurement of the concentrations of the various nutrients in the drained solution that is reused in the system. In simpler methods, where the nutrient solution is managed manually, as described in Section 2.6.1, detection of nutrient deficiencies in the solution is done through the monitoring of the EC and pH. However, as pointed out in the previous section, this method does not identify deficiencies of specific nutrients in the solution and, as a result, it becomes difficult to make individual corrections for each nutrient that is deficient or in abundance in the solution for optimal crop growth. Consequently, if certain nutrients become severely deficient in the solution, or if certain nutrients increase to excessive levels in the solution so that they restrict the uptake of other nutrients, this can result in plant nutrient deficiencies, which can easily be detected through visual diagnosis of physiological disorders that develop on the plants. Adjustments of the nutrient concentrations in the solution can be made by adjusting the solution's EC and pH values to the desired levels that are required by the plants for optimal growth. Table 2.11 indicates common symptoms of nutrient deficiencies in hydroponically grown crops, while Figures 2.8 and 2.9 show symptoms caused by nutrient deficiencies of some of the most important macronutrients in hydroponically grown lettuce and sweet basil, respectively. Detection of nutrient deficiencies in plants can also be determined through chemical analysis of plant leaves, which should be performed periodically, particularly in recirculation systems because nutrient uptake is potentially inhibited due to elevated concentrations of ions that can build-up in the solution (Bar-Yosef, 2008).

Table 2.11: Common symptoms of nutrient deficiencies in crops grown hydroponically (Advanced Nutrients, 2020).

Nutrient	Plant symptoms
Nitrogen	Plant leaves may turn a pale green, or even yellow in cases of more extreme nitrogen deficiencies. You may also notice stunted growth or a slight purple tint of the stems and on the undersides of leaves. If the nutrient solution contains excess nitrogen, plant roots may become stunted and will cause a delaying in flowering.
Phosphorous	Too little phosphorous may result in darkly hued leaves, small roots, very small flowers, and leaves that have a red or purple appearance. Signs of phosphorous deficiency may not be the result of a lack of phosphorous in the nutrient solution. It may be the result of the nutrient solution being too cold, which may decrease the uptake of phosphorous.
Potassium	A lack of potassium in the nutrient solution will result in leaves that have edges that look blackened or “burned.” They may also develop brown, necrotic spots. These signs typically appear on the older leaves first. The fruits and flowers of a potassium deficient plant may also be lighter in weight than normal.
Magnesium	This deficiency will result in the yellowing of the leaf edges. The worse the deficiency is, the yellower the edges, and more of the leaf will be affected. This is most commonly seen in tomato plants.
Calcium	Calcium deficiencies usually affects newer leaves before it affects older leaves. These leaves usually have necrotic spots, and may appear mangled and be very small in size.
Iron	A plant that is receiving too little iron will typically have yellowing of its younger leaves. In more severe cases, the leaves will become extremely pale, or almost white in colour. As with phosphorous deficiencies, iron deficiencies may be the result of the solution being too cold rather than any actual deficiency in the solution.
Manganese	Symptoms of manganese deficiencies are similar in appearance to those of iron deficiencies, except that it may affect the older leaves first rather than the younger leaves. If your nutrient solution is too rich in manganese, it might actually cause an iron deficiency because of a decreased uptake of iron.
Copper	Plants do not need much copper, and therefore copper deficiencies are very rare. However, it is possible to have too little copper, and this may result in weak, distorted, or mutated young leaves. Too much copper may decrease branching and create roots that have greater girth and are darker in colour than usual.
Boron	Not enough boron may create roots that appear “fleshy” and that are darker in colour than normal. It may also result in fruits and roots that deteriorate easily. This deficiency may also create an iron deficiency.
Molybdenum	Too little of this nutrient may darken the edges of the leaves, as well as in the curling of the leaves. Even a slight deficiency may create smaller than usual flowers.

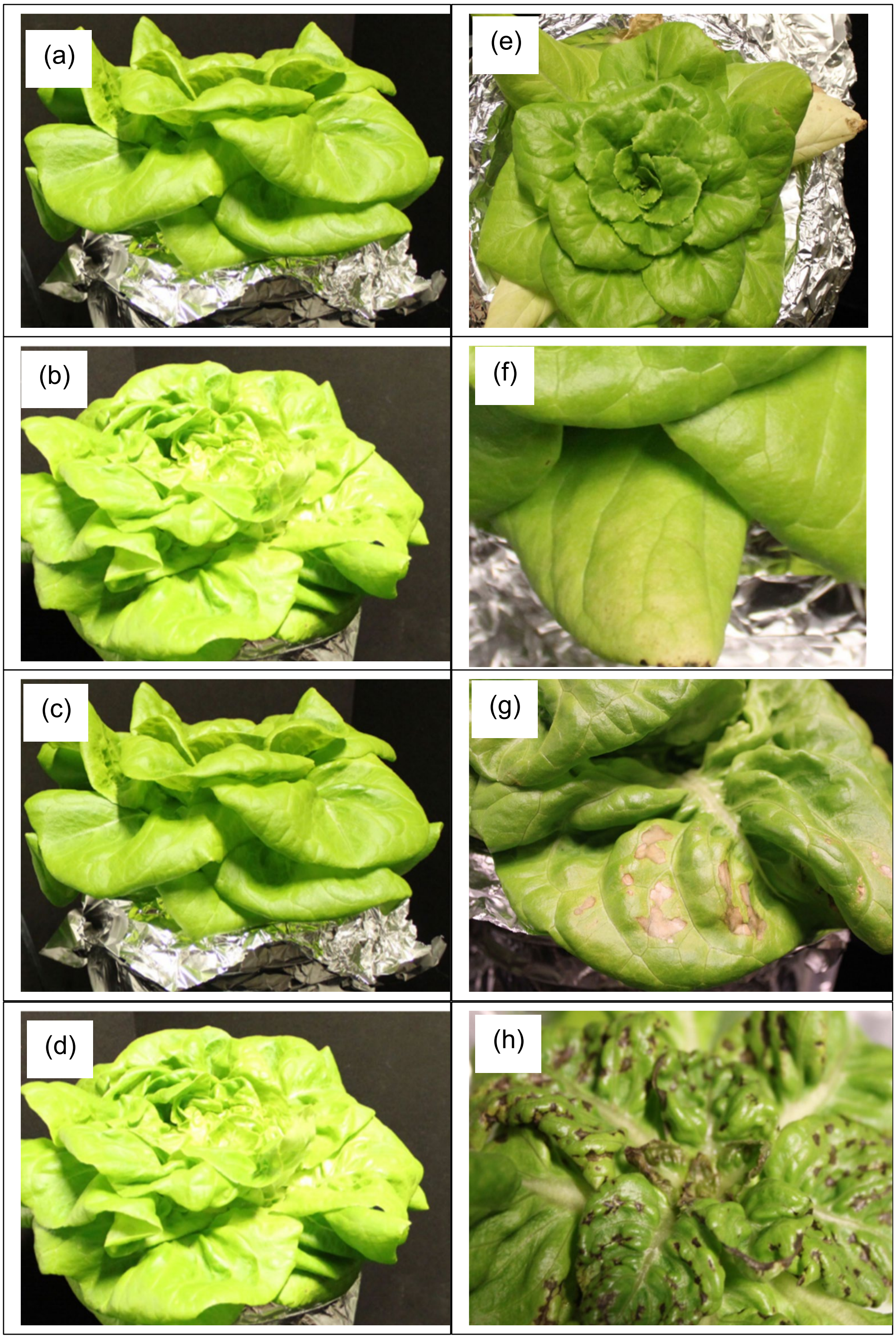

Figure 2.9: Comparison between lettuce plants growing hydroponically without any nutrient deficiencies (a, b, c and d) and symptomatic plants having macronutrient deficiencies of nitrogen (e), phosphorus (f), potassium (g), and calcium (h) (Mattson and Merrill, 2015).

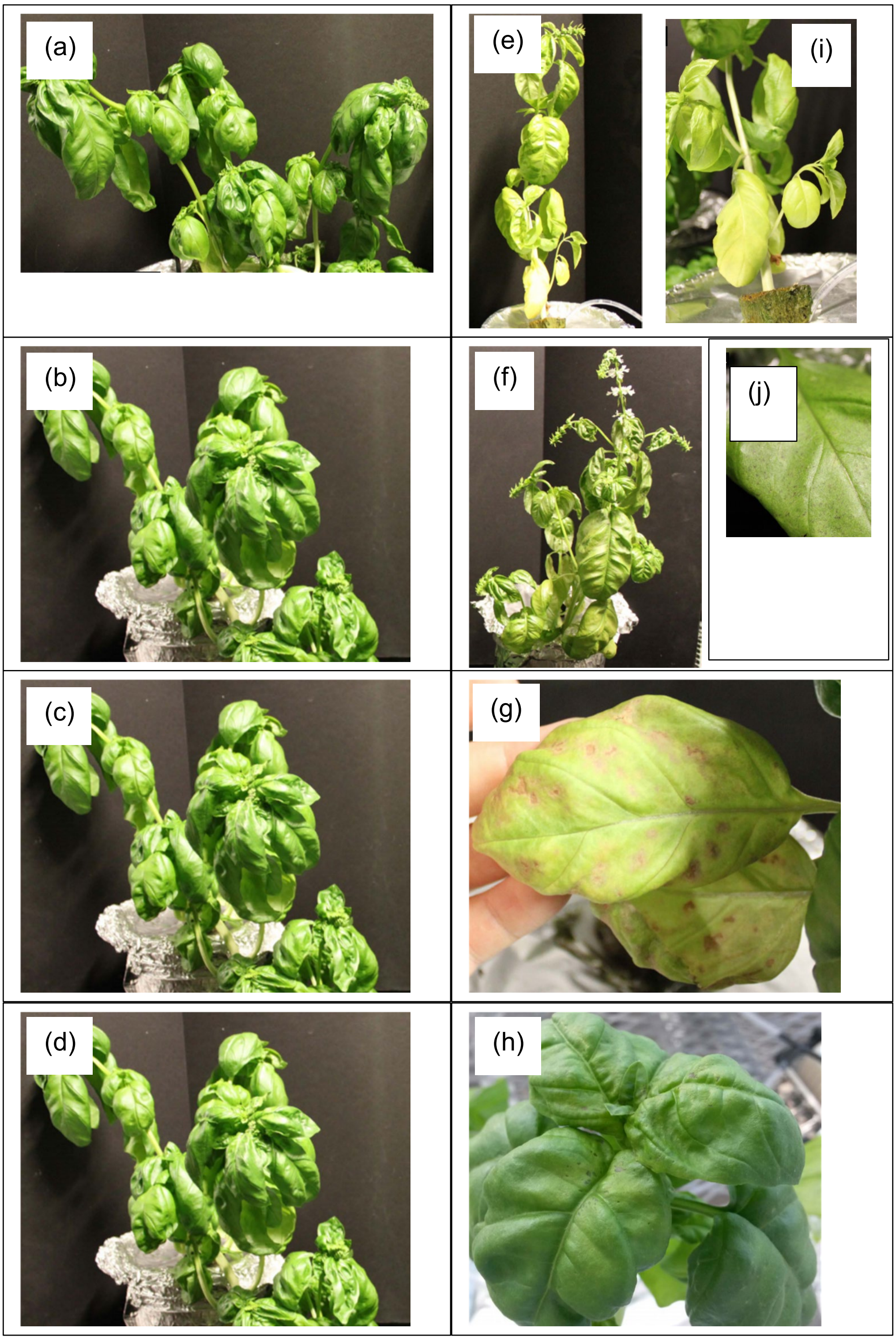

Figure 2.10: Comparison between sweet basil plants grown hydroponically without any nutrient deficiencies (a, b, c and d) and symptomatic plants having macronutrients deficiencies of nitrogen (e, i), phosphorus (f, j), potassium (g), and calcium (h) (Mattson and Merrill, 2016).

2.7.3 Water flow rates and frequencies

In active recovery systems, the water flow rate (more specifically the flow rate of the nutrient solution) influences the contact time of the roots with the recirculating solution, which in turn influences the direct uptake of nutrients by plants (Maucieri et al., 2018). In these systems, water flow cycles can be continuous as it is in the nutrient film technique (NFT) or intermittent as it is in media-based grow bed (MGB) systems, such as the ebb-and-flow technique (also called the flood and drain technique).

In continuous flow systems, higher water retention time increases the contact time of the nutrient solution with the plant roots, but it can lead to lower oxygenation rates and reduced nutrient availability if this is excessively high (Bugbee, 2004). Al-tawaha et al. (2018) investigated the ideal flow rate in an NFT system for optimization of nutrient uptake in lettuce. The study evaluated three flow rates, namely, 10, 20 and 30 L/hour, and concluded that a flow rate of 20 L/hour was the best for lettuce growth. Lettuce plants grown under a flow rate of 20 L/hour attained significantly higher plant height (28 cm), head mass (237 g), total number of leaves per plant (40), and stem height (43 cm), compared to those grown under flow rates of 10 and 30 L/hour (plant height = 22-25 cm; head mass = 135-153 g; total number of leaves per plant = 25-33 ,and stem height = 27-35 cm). This study further recommended that water movement in the NFT system, including the rate of turnover, should be adjusted to meet the specific requirements of the crop in order to ensure sufficient contact time between the roots and the water flowing through the system. In continuous water flow systems, adjustment of flow rates is more critical, compared to intermittent water flow systems. This is because the latter generally involves the use of substrates for support of plant roots with a water holding capacity which allows the nutrients to stay in contact with plant roots for longer, for more effective absorption and uptake of nutrients (Al-tawaha et al., 2016). Thus, in continuous water flow systems like the NFT, adjustment of the flow rates should be done not only for specific crops, but also for specific crop management practices. For example, higher planting densities may result in slower flow rates due to denser root volumes within the NFT pipes (Bugbee, 2004).

In intermittent water flow systems, it is more important to determine the most appropriate frequency than the rate of water flow. Chidiac (2017) examined the effect of four fertigation frequencies (1, 2, 4 and 8 hours) on lettuce grown under the ebb-and-flow technique. This study showed that irrigation frequencies significantly affected lettuce yield and physiological response. Treatments that fertigated every 1 and 2 hours resulted in significantly higher physiological and growth attributes than those fertigated every 4 or 8 hours, which is possibly explained by better root water uptake due to higher contact frequency of roots with the nutrient solution. Thus, since there were no significant differences between the 1 and 2 hour fertigation intervals, the 2 hour fertigation interval was selected as the optimal fertigation interval. This is because less frequent fertigation can save on the energy requirements for the pumping of irrigation water and result in an increase in water conservation due to reduced evaporation of water from the growing media.

2.7.4 Environmental management

Environmental management is an important factor to take into consideration in hydroponic production systems, particularly those under high tunnel production with or without temperature-controlled systems and containers. Light, temperature and humidity are the most important environmental factors affecting the yield and quality of hydroponically grown crops in partly-controlled greenhouse environments, while in fully-controlled environments, carbon dioxide (CO_2) concentration also plays a major role (Gruda, 2005; Loman, 2018).

Poor light intensity often results in reduced fruit yield and quality of hydroponically grown crops, such as tomatoes, which is attributed to etiolation and vegetative growth at the expense of the production of edible organs, leading to formation of small fruits, as well as early abortion of flowers (Krug, 1991). On the other hand, extreme light intensity or strong direct radiation can cause loss of product quality, as a result of the development of physiological and pathological disorders (Kays, 1999). Spectral quality of light is also important and can have effects on some quality parameters of greenhouse-grown vegetables. Several authors have investigated the influence of spectrum light quality on leafy vegetables, and reported a general increase in crop growth parameters due to supplementary light and exposure to either blue or red light at the end of a dark period, as well as induced accumulation of a range of secondary metabolites by exposing the crop to UV-B rays (Jansen et al., 1998; Stewart et al., 2000; Aherne and O'Brien, 2002; Nitz and Schnitzler, 2004). There is almost a complete lack of information on the light requirements for crops grown hydroponically. However, the little information that is available indicates that, in general, crops require good light intensity within the range of 600 to 800 µmol m^{-2} s^{-1} (Gruda, 2005). Since most hydroponic systems use the sun as a free source of light energy, growers can control other environmental factors, such as humidity and temperature, in such a way as to provide an adequate environment for the production of high-quality vegetables given the prevailing light conditions (Bot, 2003).

Root and air temperatures affect chemical reactions and physical properties of plants and this occurs at both on a cellular level and on a plant level (Gruda, 2005). Table 2.12 illustrates the optimum root and air temperature ranges for various hydroponically-grown crops (Thompson et al., 1998; Kafkafi, 2001; Benoit and Ceustermans, 2001; Li et al., 2002). These temperature ranges are easily maintained in temperature-controlled greenhouses through automated heating and cooling systems. In temperature-controlled high tunnels, cooling is often achieved through active ventilation, using a continuous supply of electricity to monitor and control ventilation by the opening and closing vents, and for the controlling of fans (Maboko and Du Plooy, 2015). While heating involves methods that require mechanical heating devices, which are powered by non-renewable energy sources such as oil, propane or natural gas. In non-temperature controlled high tunnels, on the other hand, heating is achieved through the use of thermal blankets, thermal curtains, plastic mulch, row covers and low tunnels for crops with determinate growth. While cooling is achieved through natural passive ventilation by means of a flap and a door that can be opened on opposite sides (Maboko et al., 2017).

Table 2.12: Optimum root and air temperature ranges for various crops grown hydroponically.

Crop species	Recommended active recovery hydroponic systems	Growth temperature range (°C)		Reference
		Root	Air	
Basil	Media-grow beds and nutrient film technique		20-25	Hasan et al. (2018)
Cauliflower	Media-grow beds		20-25 for initial vegetative growth, 10-15 for head setting	Hasan et al. (2018)
Freely lettuce	Media-grow beds and nutrient film technique	24**	15-22 (flowering over 24)*	Hasan et al. (2018)* Thompson et al. (1998)**
Cucumber	Media-grow beds		18-20 night time, 22-28 daytime	Hasan et al. (2018)
Egg plant	Media-grow beds		15-18 night time, 22-26 daytime	Hasan et al. (2018)
Pepper	Media-grow beds	> 20**	14-16 night time, 22-30 daytime*	Hasan et al. (2018)* Benoit and Ceustermans (2001)** Li et al. (2002)**
Tomato	Media-grow beds	20**	13-16 night time, 22-26 daytime*	Hasan et al. (2018)* Adams (1999)**; Kafkafi (2001)**
Bean and pea	Media-grow beds		16-18 night time, 22-26 daytime	Hasan et al. (20180
Head cabbage	Media-grow beds		15-20 (growth stops at > 25)	Hasan et al. (2018)
Broccoli	Media-grow beds		13-18	Hasan et al. (2018)
Swiss chard	Media-grow beds and nutrient film technique		16-24	Hasan et al. (2018)
Parsley	Media-grow beds and nutrient film technique		15-25	Hasan et al. (2018)

Humidity is one of the most important environmental factors that influences the water status of crops grown hydroponically, particularly in greenhouses. This in turn affects all processes that are associated with transpiration, including water balance, transpirational cooling and the translocation of nutrients (particularly calcium) from plant roots to shoots (Gruda, 2005). Optimum humidity levels for greenhouse-produced crops are generally in the range of 60 to 80% (Li et al., 2002). Under extreme humidity levels (95% and above), increased flower abortion and reduced pollen viability on peppers and tomatoes has been observed, leading to a reduced number of fruits per plant, as well as reduced fruit quality due to a high incidence of physiological and pathological ripening disorders and fungal diseases (Mulholland et al., 2001; Li et al., 2002). Under high humidity levels, Dorais et al. (2001) also noted that tomato fruits were generally smaller, softer and misshapen, with a higher incidence of gold specks. However, there is evidence that crops benefit from high levels of humidity during the night, when the stomata are closed. Bradfield and Guttridge (1984) observed greater calcium uptake by the fruit when nights were humid rather than dry. Similarly, high air humidity during the night appeared to prevent calcium deficiencies in lettuce (Collier and Tibbitts, 1982). Conversely, Bakker et al. (1987) concluded that fruit production and quality in cucumber is improved when humidity is set relatively high during the daytime and relatively low during nighttime. Thus, the impact of high humidity in greenhouse production is rather crop-specific. Most of the research investigating the effect of humidity on crop production has been done on tomato, while information on other crops is generally scarce (Gruda, 2005). Several factors influence humidity levels in greenhouses, including internal air exchange with the atmosphere, water condensation at the root level, as well as on the plants. In cool climatic environments, the most practical method of controlling humidity is to increase ventilation by opening the vents and/or rolling-up of the sides, or even opening of large doors on each end wall. Other ways to increase ventilation to reduce humidity include using end-wall exhaust fans combined with inlet louvers. By doing so, much of the water vapour is lost with the escaping heat, and in exchange, drier cooler air is drawn into the structure. This should be done in combination with air circulation using horizontal airflow fans, to ensure a uniform mixing of the air inside the greenhouse (Callahan, 2019). While, in hot desert areas, humidity levels in the greenhouse can be controlled simultaneously with air temperature levels, by means of ventilation, irrigation and solar radiation shielding (Hirasawa et al., 2014). Carbon dioxide on the other hand, is generally piped directly into the facility to reach the required levels for plant growth (usually 800-1200 ppm). This is done by injecting pure CO_2 from canisters, or by using a generator that runs on natural gas or propane (Loman, 2018).

2.7.5 Water quality aspects

Water quality is an important determining factor in hydroponics cultivation, since it is through water that nutrients are dissolved and transported to the plant. However, water also dissolves a lot of impurities that can be harmful to plants. These impurities cannot be easily detected visually. Poor water quality can lead to a number of plant growth problems, including stunted growth, mineral toxicity or mineral deficiency symptoms, build-up of unwanted elements in plant tissue, bacterial contamination, etc. The most important quality parameters to take into consideration in hydroponics production include chlorine and chloramines, bacteria and pathogens, minerals and water hardness (Schwarz et al., 2004). Water supply for hydroponics production can be sourced from rainwater, surface water, including dam water, and ground water that includes borehole and water from wells (Van Os et al., 2016). Thus, before starting a hydroponics project, it is important to know the quality of the water source in terms of the presence of specific ions, phytotoxic substances or organisms, and substances or organisms clogging the irrigation systems. This includes conducting a detailed chemical analysis of the water source (pH, electrical conductivity – EC, ammonium – NH_4, potassium – K, calcium – Ca, magnesium – Mg, ammonia – NO_3, sulphate – SO_4, dihydrogenphosphate – H_2PO_4, bicarbonate – HCO_3, iron – Fe, manganese – Mn, zinc – Zn, boron – B and cupper – Cu). (Table 2.13) illustrates the degree of restriction on the use of water of a certain quality for hydroponics or soilless crop production.

Table 2.13: Components of water and their limits for use in hydroponics (de Kreij et al., 1999).

Parameter	Units	Degree of restriction on use of water		
		None	Slight to moderate	Severe
EC	mS cm^{-1}	0-0.75	0.75-2.25	>2.25
Bicarbonates	mol m^{-3} (ppm)	0-2 (0-120)	2-6 (120-360)	>6 (>360)
Nitrates	mol m^{-3}	<	0.5-2	>2
Ammonium	mol m^{-3}	≈0	0.1-1	>1
Phosphorus	mol m^{-3}	<0.3	0.3-1	>1
Potassium	mol m^{-3}	<0.5	0.5-2.5	>2.5
Calcium	mol m^{-3}	<1.5	1.5-5	>5
Magnesium	mol m^{-3}	<0.7	0.75-2	>2
Sodium	mol m^{-3}	<3	3-10	>10
Chloride	mol m^{-3}	<3	3-10	>10
Sulphates	mol m^{-3}	<2	2-4	>4
Iron	mol m^{-3}			>90
Boron	mol m^{-3}	<30	30-100	>100
Cupper	mol m^{-3}			>15
Zinc	mol m^{-3}			>30
Manganese	mol m^{-3}			>10

The quality of rainwater is in general well suited for hydroponic cultivation, without any problems with nutrient concentration, and bacterial and algal development (Schwarz et al., 2004). Whereas surface water from rivers, lakes or canals might have a variable (from excellent to very poor) chemical quality. While groundwater, similarly to municipal tap water, can contain large amounts of salts, which if not treated prior to its use, can have a negative effect on crop productivity by causing toxicity to plants, or even influence nutrient uptake (Mahjoor et al., 2016; de Lira et al., 2019). de Lira et al. (2019) evaluated groundwater with high concentrations of different ions (calcium sulphate, magnesium chloride, calcium chloride, sodium chloride and magnesium chloride) on watercress and Chinese cabbage production using the NFT hydroponic system. Results from their study showed that the differences in the quality of water used directly affected the growth and yield of the watercress and Chinese cabbage plants, with water containing calcium chloride being the most suitable for the production of watercress, while for Chinese cabbage none of the water qualities tested was found suitable.

Poor quality water, containing high levels of bicarbonates (3-7 mol m^{-3}), can be treated by adding acid to reduce the level of bicarbonates to 0.5 mol m^{-3} prior to its use in hydroponics. Other elements that are present in high levels in poor quality water, such as sodium (which interferes with the uptake of calcium and magnesium) and calcium (which often creates precipitates in stock solution preparation with sulphates) can be reduced using a reverse osmosis water purifier, or by mixing with rainwater (Van Os et al., 2016). Also, by knowing the nutrient composition of the water supplied to the plants, growers can try to balance the nutrients added into the system in order to minimize problems associated with the presence of high quantities of specific elements.

2.7.6 Pest and disease control

Active recovery hydroponic systems require appropriate crop and systems management in order to limit the spread of root infesting pathogens, since the nutrient solution is continuously recirculated through the system (Schnitzler, 2004). Even though these systems are more prone to infestations than non-recovery systems, there are still obvious advantages in implementing them, since the drained nutrient solution is re-used, with water and fertilizer savings, as well as good environmental stewardship (Ehret et al., 2001). Growers must ensure that good quality water is used in the production system, as discussed in Section 2.6.5. In addition, it is important to use well-balanced nutrient solutions, as well as select appropriate substrates for seedling preparation. If these conditions are not met, the crop can be stressed and, therefore, become more susceptible to pests and diseases. It is for this particular reason that inert growing media, such as gravel, rockwool and expanded clay, are generally more ideal for active recovery hydroponic systems, as they have fewer problems of phytopathogen contamination due to their manufacturing processes, as compared to the organic ones (Maucieri et al., 2019).

Phytopathogenic fungi create some of the biggest problems in recovery hydroponic systems due to the fact that they are well adapted to the aquatic surrounding and are able to produce zoospores in the nutrient solution around the plant roots. Pythium and Phytophthora are some of the most commonly found phytopathogenic fungi species affecting lettuce and tomato grown in NFT systems (Schnitzler, 2004). Tomatoes grown in soilless culture are also susceptible to several bacterial diseases and nematodes, such as Meloidogyne incognita (Amsing and Runia, 1995). Virus infections are other potential threats that can spread in hydroponics. Some of the most common viruses include lettuce big-vein virus (LBVV), tobacco necrosis virus (TNV) and Melon necrotic spot virus (MNSV), which can be transported in the nutrient solution of recovery hydroponic systems from plant to plant. Although problems of phytopathogen contamination are lower in hydroponics production when compared to open field production, preventative sanitation measures are still of primary importance in greenhouses to control the spread of pests and diseases. This includes the use of clean substrates, decontamination of greenhouse structures and all other sources of infestation. In addition, growers can adjust environmental growth conditions, such as root zone temperatures, to optimal levels for crop growth as described in Section 2.6.4. Another very useful and commonly applied method to control diseases in recirculating hydroponic systems is to disinfect the nutrient solution. Various methods and technologies have been developed for this purpose, as described in Table 2.14. Van Os (2009) compared the performance of some chemical and non-chemical treatments to disinfect nutrient solutions of recirculating systems. He found that heat treatment and UV radiation are the best options for large-scale production (> 2.0 ha), while for smaller companies (< 1.0 ha), slow sand filtration is a good option. Nonetheless, in a separate study, Mine et al. (2000) found contradictory results after testing the effect of the slow sand filtration method for disinfection of a NFT nutrient solution for the growing of tomatoes. The slow sand filtration method affected concentrations of some macro- and micro-nutrients, which ultimately had a negative impact on the growth and physiological responses of the crop. Hydrogen peroxide, on the other hand, has been reported to be an affordable and efficient method for disinfection of an aquaculture recirculating system, particularly when applied at low dosages of 13-15 mg/L (Pedersen et al., 2012; Pedersen and Pedersen, 2012; Fredricks, 2015). Further research is however required to investigate the potential of hydrogen peroxide for the disinfection of nutrient solutions of recovery hydroponic systems, and its related impact on crop productivity and on a farmer’s profitability.

Table 2.14: Advantages and disadvantages of the most popular nutrient solution disinfection methods in recovery hydroponic systems (Runia and Amsing, 2001; Van Os, 2010; Stewart-Wade, 2011).

Disinfection method	**Doses**	**Advantages**	**Disadvantages**
Heat treatment	95˚C for 30 s or 85°C for 3 min	High efficacy	High investment and running costs (only for large-scale production)
UV-C radiation	100-250 mJ/cm^2 UV-C	Moderate efficacy and investment cost	Sometimes unreliable results; needs pre-filtration; iron chelate breakdown
Membrane filtration	Pores size: 0.05 μm for *Fusarium*; 0.1 μm for *Verticillum*	High efficacy	Very expensive; low lifetime of filter membrane
Ozone	10 $g\ m^{-3}\ h^{-1}$	High efficacy	Expensive; needs preventive filtration and acidification; iron chelate breakdown
Chlorine	2 ppm di Cl per 1' for P. Cinnamomi	High efficacy; used for sanitation of greenhouse structures and devices	Difficulties to establish the efficacy doses; acidity and organic compounds influence the efficiency
Hydrogen peroxide	100 ppm for *Fusarium* spp.	Low investment costs	Does not kill the nematodes completely; iron chelate breakdown
Slow filtration	Flow rate of 100-300 $L\ m^2\ h^{-1}$ Sand grain size: 0-2 mm	Low investment costs; suitable for low technology, small-size greenhouse operations	Eliminates completely zoosporic fungi and only partially *Fusarium*, viruses and nematodes

2.8 Crop management

2.8.1 Plant spacing

Plant spacing is the space defined between planted plants and rows, and it is used to get the overall plant population per unit area. It has been an important aspect in agriculture because it is used to optimise crop yield and quality (Maboko et al., 2011). Understanding the crop's response to plant density is vital for growers to maximize crop yield. For instance, Maboko and Du Plooy (2009) reported that planting too high or too low numbers of plants per unit area could result in lower yields and quality, as compared to optimum planting densities (Table 2.15). In the context of soil-based agriculture, the principle is that, too high planting densities could result in increased competition for water, solar radiation and nutrients. This ultimately results in poor biomass accumulation and eventually poor yields and quality of produce. In contrast, using too low planting densities could result in low yields per total cultivated area. Therefore, optimal planting densities should be determined for specific crops. However, in hydroponics, it is widely reported that increased planting densities increases crop yield due to a non-limited supply of water and nutrients to the crops. For instance, Maboko and Du Plooy (2009) studied the optimal planting density for lettuce in a GFT system. The results demonstrated that major plant growth variables, such as plant height, leaf area and leaf number, increased with an increase in plant density. The compacted spacing, which was 50 and 40 plants/m^2, produced taller plants, with an average height of 197.1 mm and 192.1 mm, respectively, when compared to the widely spaced plant densities of 20 and 25 plants/m^2 that resulted in shorter plants with heights of 147 and 159 mm, respectively. Many authors reported that this is attributed to increased competition for solar radiation and more energy being channelled for vegetative growth (Maboko et al., 2011). Therefore, these effects are good for leafy vegetable and herb growers, because the stimulated vegetative growth is directly related to an increase in the actual production. In fruiting vegetables, high planting densities may have the opposite effect on the crop's marketable yield and quality. For instance, Maboko et al. (2011) reported higher unmarketable yields in tomato production planted at a higher plant density of 2.5 and 3 plants/m^2, as compared to 2 plants/m^2. This was due to a greater number of fruits that were graded as extra-small sized fruits. This was attributed to stimulated vegetable growth due to competition for light, and a greater allocation of carbohydrates to vegetative growth rather than reproductive growth and fruit formation and development (Maboko et al., 2017).

Table 2.15: Optimum plant spacing or planting densities for selected, commonly grown crops in active recovery systems.

Species	Plant spacing/ densities	Active recovery system	References
Swiss chard	40 plants/m^2	GFT	Maboko and Du Plooy (2013)
Mustard Spinach	25 plants/m^2	GFT	Maboko (2013)
Tomato	11 plants m^2	NFT	Cardoso et al. (2018)
Peppers	0.3 m × 0.3 m	NFT	Furtado et al. (2017)
Strawberry	29 plants /m^2	NFT	Ramírez-Arias et al. (2018)
Lettuce	50 plants/m^2	GFT	Maboko and Du Plooy (2009)
Basil	40 plants/m^2	GFT	Maboko and Du Plooy (2013)

2.8.2 Plant spatial arrangement

Spatial arrangement is the distribution of plants in a specified space. This describes how plants are put together in a hydroponic structure without compromising aeration and sufficient sun rays reaching both sides of the plants. The inception of environmental-controlled agriculture has since made this aspect unnecessary by providing controlled aeration and light to plants artificially. However, it is still relevant to low-cost greenhouse and tunnel structures, as well as shade nets. There is almost a complete lack of information on the plant spatial arrangement in hydroponic systems, which may limit the optimization of light/radiation use efficiency of crops grown in these systems, especially because of the limited space that is available for plant growth. Generally, crop spatial distribution is achieved by a combination of inter-row spacing and plant density (Bezerra et al., 2016). In a soil-based production study, Bezerra et al. (2016) highlighted that an increased plant density of 30 000 plants per hectare with lower inter row spacing of 0.30 m increased interspecific competition for environmental resources such as radiation, water and nutrients. Interestingly, it was observed that leaf area in sunflower was reduced due to reduced light interception. Contradictory results were observed in a floating hydroponic system in which lettuce was cultivated (Gonnella et al., 2003). Gonnella et al. (2003), studied the arrangement of four and eight plants per row of 0.17 m in length, planted with 316 and 620 plants/m^2 as plant density, and found that the eight plants per row treatment significantly increased overall yield and leaf dry mass. The contradictory effect of plant density between soil-based production systems and soilless hydroponic systems may be due to the source of nutrients. For instance, in soil-based agriculture, reduced growth due to intraspecific competition is common because nutrients are not readily available for the growth of the increased plant population. In hydroponic production nutrients and minerals are readily available in a form suitable for root uptake and are continuously provided. Nonetheless, a common factor in the studies is that the studies were done on horizontal surfaces where radiation should be better compared to vertical farming methods. Kalantari et al. (2017) reported that vertical farms without the installation of environment controlling technologies that will provide artificial radiation and aeration are more vulnerable to limited solar radiation and aeration. Therefore, spatial arrangement should be employed in vertical farming to ensure production efficiency (Douglas et al., 1990). Furthermore, production in shade nets and high tunnel structures should employ spatial distribution for better light interception (Douglas et al., 1990).

2.8.3 Trellising

Trellising is a mechanical form of plant support designed to train the growth of indeterminate crops up the twine, in a certain growth direction (Maboko et al., 2011). The accelerated growth of crops, due to favourable growing conditions provided in hydroponics, needs to be controlled in order to preserve the yield and quality of crops (Maboko et al., 2017). It is a methodology that was practiced even in soil-based agriculture way back before the inception of hydroponics. In soil-based agriculture, it was generally practiced on fruiting trees such as grapes, whereas in hydroponics this is done in crops such as tomatoes and peppers. Tomatoes have tender stems and should be trellised when they reach a length of 50 cm (Maboko et al., 2017). They are trained to a single stem and trellised through layering and string. Plants are twined through cables as they grow up, similar to cucumbers and green beans (Figure 2.11). Trellising ensures that the stems of the tomato plants remain upright to avoid touching the growing floor area and ultimately avoid contracting of diseases and prevents bruising of the fruits. It has several advantages that includes easier to spot and pick mature and ripened fruits, allows more light interception by older leaves, and allows for higher planting densities (Maboko and Du Plooy, 2008). There are several trellising methods for cucumbers, depending on production systems and preferences of growers. For instance, there are cucumbers that can be trellised using the vertical trellising method, the inclined V trellising method and the Arch training system. Figure 2.11 shown the vertical trellising method, where the main plant stems are trellised vertically from the pots to grow parallel through pruning of any lateral growth. The inclined V trellising method twine plants which form a V shape from the bottom up, usually planted in a zigzag pattern to maximize space usage in a greenhouse (Figure 2.10). The last method is called the Arch Training System which allows one plant to grow from one side to the other without pruning. This is done with the support of horizontal that are positioned parallel and perpendicularly to the greenhouses structure (CHF, 2018). These methods also go hand in hand with pruning to train crops. In tomato production, auxiliary buds are pruned to maintain single stems that are trellised with cables (CHF, 2018).

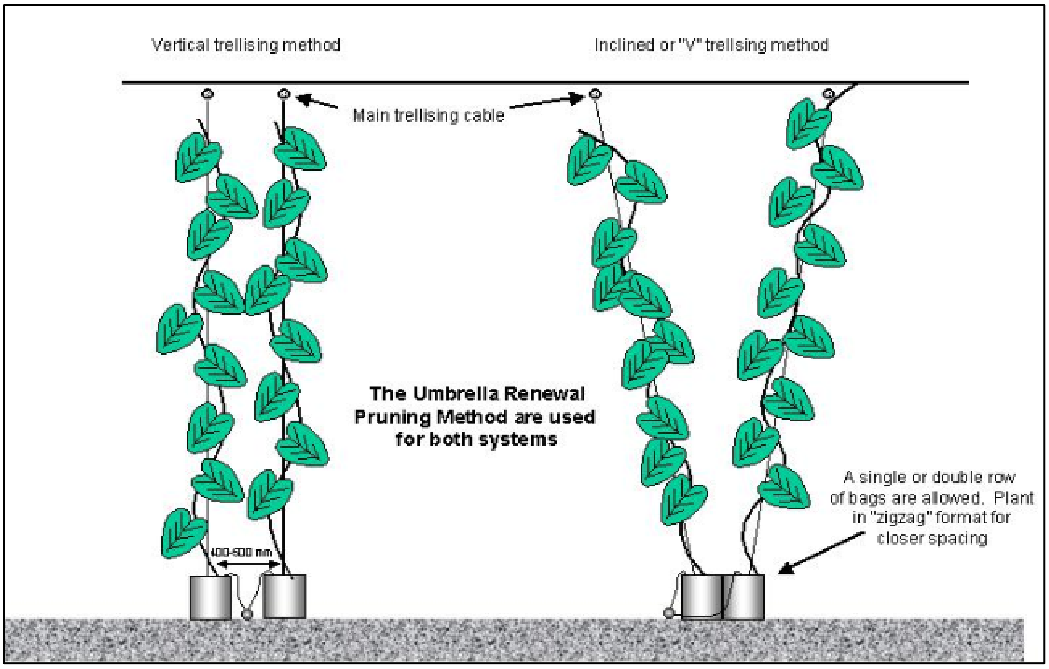

Figure 2.11: Trellising methods that can be employed in fruiting crops like cucumber: the vertical trellising method (left) and the inclined V trellising method (right) (CHF, 2018).

Plants are allowed to grow up through the trellising twine and reach the supporting wires at the top and bend over them towards the other side of the plant pot (Figure 2.11). However, in this method, lateral growth may not be pruned. Fruits will be hanging down and can easily be harvested harvesting (CHF, 2018).

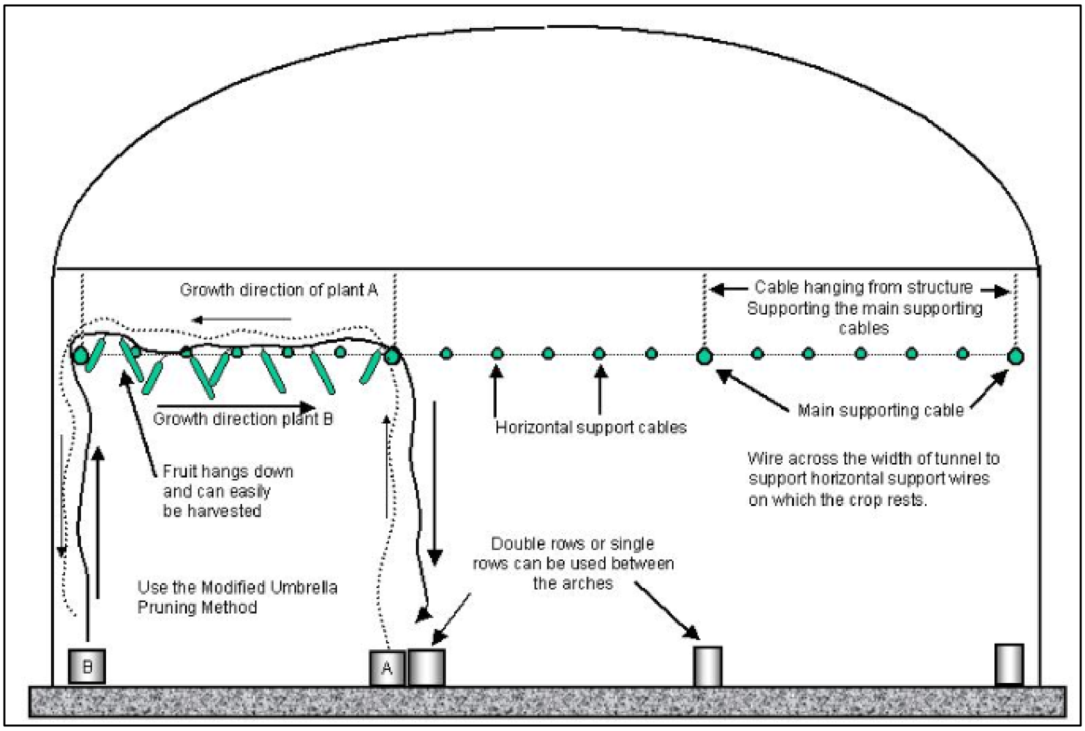

Figure 2.12: The Arch training and trellising method: well suited for fruiting crops like cucumber (CHF, 2018).

2.8.4 Pruning

Crop pruning is a purposeful removal of a crop's branches, flowers, stolons, diseased leaves, or fruit management techniques. It is a practical way of balancing and maintaining the progression between vegetative and reproductive growth (Maboko et al., 2012). Crop pruning is important and is practiced by both soil-based and soilless growers. However, it is critically important in hydroponics because growth rates are generally higher in these systems compared to soil-based cultivation. Therefore, regular and mandated pruning is necessary, otherwise, excessive growth could be uncontrollable, which could have a negative impact on crop yield and quality, particularly in hydroponic systems, in which plants are cultivated under high planting densities in limited spaces (Maboko et al., 2011). The anchoring ability of roots in hydroponically grown plants is not as strong compared to plants grown in soil because roots do not spread out in search of nutrients. Thus, poor anchorage cannot support a high load of forage in crops such as tomato. Hence, fruit pruning is used to control fruit load. Fruit load influences partitioning between vegetative and reproductive plant growth through mutual competition for assimilates (Maboko et al., 2012). Too high fruit loads can exhaust the plant, resulting in fruit and flower abortion and cyclic produce. Pruning is also important for greenhouse production because, due to the high investment costs, growers need to use the area very efficiently. Therefore, pruning allows for high-density planting and higher quality products (Maboko et al., 2011). Tomato forms part of the important crops eligible for pruning in hydroponic cultivation. Pruning ensures proper and efficient translocation of assimilates in the growth and development of fruits and the main stem. It is done for both determinate and indeterminate varieties, and for plants that continue to grow and flower (Maboko et al., 2017). Maboko et al. (2012) reported that, without pruning, considerable crop losses could be realised. The best way to prune tomatoes is to maintain one main stem and remove all suckers (side shoots). Hand removal of suckers of 2 to 2.5 mm in length, once a week, is the best method for the pruning of tomatoes (Maboko and Du Plooy, 2008). Similarly, crops such as strawberries have runners which should be checked and pruned regularly to increase assimilate efficiency. The lateral growth that is pruned can be used as crop propagation material. Pruning of strawberry plants also helps to reduce crop forage mass when planted in vertical farming rafts (Kumar and Saini, 2020). Green beans are fast growing plants that should be pruned and trained at an early growth stage. It involves cutting/ pruning lateral growth and maintaining apical growth trellised using a string (Kumar and Saini, 2020). Pepper pruning is quite different from tomato pruning, since it produces more than one main stem or multiple stems. Therefore, the stems should be pruned to a standard optimal number of main stems to achieve the best results. Alsadon et al. (2013) studied the effects of pruning of the stems, flowers and fruits of sweet pepper. Results from their study demonstrated that sweet pepper plants pruned to a single stem resulted in a significant increase in early fruit yield, fruit size and fruit quality traits due to a reduced total number of stems per plant. However, Maboko et al. (2012) contradicted these results, showing that plants pruned to four stems had significantly higher total yields during experiments conducted over two seasons, as compared to three or two stems. The contradiction might be due to the pruning of young flowers (first crown flower and second-order flowers) in the study conducted by Alsadon et al. (2013). Pruning of young flowers might have encouraged robust initial vegetative growth in one stem pruning (Alsadon et al., 2013). Therefore, it is important to note the interrelationships of crop organs when pruning (Maboko et al., 2012; Alsadon et al., 2013).

2.8.5 Pollination

Pollination is a process that takes place in the flower, where pollen grains from the male anther of a flower are transferred into the female stigma for fertilization (Piovesan et al., 2019). It is an essential process for crops to avoid crop losses by ensuring high fertilization rates. Up to 50% of crop produce could be lost due to flower drop as a consequence of poor pollination (Piovesan et al., 2019). Therefore, this process should be highly prioritised for fruiting crops. It is a natural process that is facilitated by insects or birds for outside growers. It is a process that is important for fruiting crops such as tomatoes, strawberries and peppers. However, in a protected environment it could be a challenge for pollinating insects to gain access (Pulela et al., 2020). Furthermore, crops such as tomatoes, which are normally pollinated through pollen being transported by wind, experience difficulties in greenhouse production. This is because air movement in a crowded greenhouse is usually not enough to ensure good pollination. Hence, hydroponic growers often opt for mechanical pollination, which involves shaking or vibrating flower clusters at least every two days when conditions are optimal (De Miranda et al., 2014). In the case of mechanical and electric vibrator pollination, the operation should be done when humidity and temperature are ideal according to crop environmental requirements. Incidentally, some devices can be used for manual pollinations such as battery-operated pollinating tools (Yang and Kim, 2020). The best strategy is, however, to attract pollinators into the cultivation environment, either by planting crops such as sunflowers, lavender and mint next to the growing structure (De Miranda et al., 2014).

2.8.6 Crop planting and harvesting frequency

Planting frequency refers to the possibility that the planting interval can be achieved within one season or within a year according to the crop's life cycle (Maboko et al., 2017). Hydroponics cultivation has attracted many growers due to the ability to shorten the crop's life cycle (Maboko and Du Plooy, 2009). The life cycle is shortened due to the rapid growth of plants in hydroponics. The rapid growth is the result of ideal growing conditions provided for the crops. Furthermore, crop type and harvesting methods are also important. For example, crops such lettuce are only harvested once before being torn out and replanted (Olfati et al., 2011). Other crops, such as kale, mustard, chives, chard, and some herbs can be harvested multiple times (Table 2.16). Therefore, a shortened life cycle is particularly important for lettuce and other heading crop producers with limited resources. Hydroponics production is reported to reduce the normal growing life cycle by 25%, and crops can be planted more than three times per season (Gilmour et al., 2019). This may be great for heading lettuce growers which can be planted up to eight times, however it may require a more intensive crop management. Lettuce leafy cultivars are good alternatives or parallel options for sustainability. Most growers are reported to prefer crops such as kale and basil that are not planted frequently and that are harvested over an extended period (Gilmour et al., 2019). According to Cardoso et al. (2018), year-round and cool season tomato growers usually practice two plantings per year, with multiple harvests per planting.

Crop harvesting frequency is an important aspect of crop husbandry in soilless culture (Olfati et al., 2011). It is generally overlooked in the literature, although farmers are always greatly interested in the crop harvesting frequency. It is because crop harvesting frequency is directly affected by market demands (Olfati et al., 2011). Harvesting frequency depends on the type of crop being produced, either leafy or fruiting vegetables. Leafy vegetables need time to regenerate and to allow new growth, whereas in fruit crops harvesting can be done in a short space of time (Table 2.16). Leaf harvesting frequency affects nutrients assimilation by the plant and ultimately plant growth. Since leaves are the primary organs for the photosynthetic functions of the plant, frequent pulling of leaves in a form of harvesting, often results in a reduction of photosynthetic activities and biomass needed for crop growth (Mampa et al., 2013). It is a management characteristic that should be timed and optimized for each crop. Maboko and Du Plooy (2019) studied the harvesting frequency of Chinese cabbage on a 7- and 14-day frequency. The results highlighted that a 14-day harvesting frequency significantly improved leaf area, leaf fresh and dry mass, as well as the number of inflorescences when compared to a 7-day harvesting frequency. In contrast, leaf number was higher at a 7-day harvesting frequency. The noticeable result was that harvesting at a 7-day frequency resulted high leaf numbers when compared to a 14-day harvesting frequency. However, the number of leaves in the 7-day harvesting frequency were significantly smaller when compared to the 14-day harvesting frequency. This may be due to the growth stimulation by harvesting at reduced time intervals where the plants dedicate carbohydrate assimilation to recover rather than to growth (Maboko and Du Plooy, 2013). Fruiting crops such as tomatoes and strawberries can be harvested two to four times per week, depending on the cultivar. Cultivar selection is also an important consideration for crop yield per season (Maboko and Du Plooy, (2013).

Table 2.16: Planting and harvesting frequency, as well as total possible harvests for leafy and fruiting crops cultivated in active recovery systems.

Crop type	Planting frequency	Harvesting frequency	Total possible number of harvests per plant	References
Leafy crop				
Lettuce	3-4 times per season	-	1	Maboko and Du Plooy (2009)
Swiss chard	2 times per year	14-day interval	6	Maboko and Du Plooy (2013)
Mustard	2 times per year	14-day interval	7	Maboko (2013)
Spring onion	2 times per season	14-day interval	2-3	Kane et al. (2006)
Basil	2 times per season	14-day interval	6	Raimondi et al. (2006)
Fruiting crop				
Tomato	2 times per year	2-3 days interval	8-10	Cardoso et al. (2018)
Strawberry	Once per year	2-3 days interval	15	De Miranda et al. (2014)
Peppers	Once per year	1-3 days interval	8-10	Furtado et al. (2017)
Cucumbers	Once per season	1-3 days interval	8-10	Maboko et al. (2017)

2.8.7 Management of the nutrient solution

Active recovery hydroponic systems are an attractive form of hydroponic cultivation due to the ability of reusing the water and nutrients (Putra and Yuliando, 2015). The systems supply sufficient nutrients and water in a controlled manner, with minimal leaching and environmental contamination. Practically, the roots are exposed to a continuous supply of water and minerals that are recirculated (Sharma et al., 2018). The mineral content solution will drop as the recirculation continues due to nutrient uptake by plant roots. Therefore, the mineral content should be frequently replenished. The reuse and recirculation of the nutrient solution is a huge advantage for active recovery hydroponic systems in the context of resource use efficiency (Putra and Yuliando, 2015). However, there are considerable aspects of nutrient management that should be mastered to ensure that the crops are not exposed to nutrient deficiencies/toxicities. There are three important characteristics to manage the nutrient solution, which are electrical conductivity (EC), pH and the nutrient concentration ratio. Electrical conductivity is a measure of total mineral elements dissolved in a solution. It is important to measure this because too low concentrations of mineral elements will result in mineral deficiencies and retard plant growth, whereas too high mineral concentrations result in saline conditions. But, in many instances, producers try to avoid nutrient deficiencies by adding more fertilizers (increase the EC) without caution. However, Yang and Kim (2020) demonstrated that increasing the EC from 1.0 to 6.0 mS cm^{-1} reduced the fresh mass of tomato shoots and fruit. Furthermore, it was found that plants grown at an EC of 6.0 mS cm^{-1} experienced a 50% reduction in yield compared to plants grown at an EC of 1.0 mS cm^{-1}. Nonetheless, it is well known in soil-based agriculture that saline conditions (with high EC levels) reduce yield and plant growth in tomatoes and other crops (Putra and Yuliando, 2015). The ideal nutrient solution varies across different hydroponic systems, crop species, growth stage, and planting density, but it is typically between 1.0 and 3 mS cm^{-1} (Yang and Kim, 2020). Generally, optimal EC values for different active hydroponics crops ranges from 1.5 to 2.5 mS cm^{-1} (Figure 2.12) (Sharma et al., 2018). However, it is important to note that the value of the EC does not guarantee the presence of mineral elements in the solution, but the overall salt content (Yang and Kim, 2010). The ideal EC and pH ranges for different crops are shown in (Table 2.17).

Table 2.17: Optimal electrical conductivity (EC) and pH ranges in the nutrient solution for various crops grown in active recovery systems.

	Vegetative growth		**Reproductive growth**		**References**
	EC ($mS\ cm^{-1}$)	pH	EC ($mS\ cm^{-1}$)	pH	
Strawberry	1.2-1.5	5.5-6.0	1.8-2.5	5.5p6.0	Kumar and Saini (2020)
Lettuce	1.3-2.5	5.5-6.0	–	–	Djidonou and Leskovar (2019)
Kale	2.5-3.0	6.5-7.0	–	–	Daryada et al. (2019)
Tomato	2.0-2.5	5.8-6.1	3.0-4.0	5.8-6.1	Sharma et al. (2018)
Peppers	1.8-2.3	5.5-6.1	2.3-3.0	5.5-6.1	Sharma et al. (2018)
Cucumber	1.7-2.0	5.0-5.5	2.0-2.5	5.0-5.5	Pedrosa et al. (2011)
Basil	2.0-2.5	5.5-6.5	–	–	Walters and Currey (2019)
Parsley	1.8-2.2	6.0-6.5	–	–	Sharma et al. (2018)
Swiss chard	2.0-2.4	5.8-6.1	–	–	Maboko et al. (2012)

The pH of the nutrient solution is another important aspect of solution management that determines nutrient mineral availability for uptake by the roots (Lee et al., 2016). It is a measure of acidity and alkalinity of the nutrient solution. It is a parameter that indicates the concentrations of free ions H^+ and OH^- in the solution at a pH range of between 0 and 14 (Sharma et al., 2018; Yang and Kim, 2020). The pH values that approach zero are regarded as acidic, whereas values that approach 14 are regarded as alkaline. The pH of the solution is the most crucial characteristic because it determines nutrient availability in the solution for uptake by plant roots. Various studies that examined the optimum pH for hydroponic lettuce production reported decreases in leaf area, shoot dry weight, leaf length and width, and stomatal conductance due to the pH not being maintained in the specified range (Yang and Kim, 2020; Maboko et al., 2011; Cardoso et al., 2018). However, many studies reported that a pH range between 5.5 and 6.5 is suitable for most crops grown hydroponically (Sharma et al., 2018; Maboko et al., 2011; Maboko et al., 2017). Generally, freshwater pH readings between 6.8 and 7.6 should be buffered to meet the crop's pH requirements (Lee et al., 2016). Different buffering agents are normally used in hydroponics, which include nitric acid, sulphuric acid and vinegar (Saparamadu et al., 2010).

The third factor of nutrient solution management is the nutrient ratio which plays a central role in plant nutrient uptake. This is due to the reactive capabilities of mineral elements. Determination of the most favourable nutrient ratio during crop growth is important, because it will affect the partitioning of carbohydrate translocation to plant organs. Therefore, the most important nutrient ratio is the N:K (nitrogen: potassium) ratio, which affects vegetative and reproductive growth of plants, particularly of fruiting crops. In this instance, the content of the nutrient solution for fruiting crops should be formulated to either stimulate vegetative or reproductive growth. Whereas for leafy vegetables, this ratio should cater for crop growth throughout the entire cycle (Table 2.18). The formulation of nutrient solutions for fruiting crops is complex since it should be adapted according to the growth phase of the crop. Cardoso et al. (2018) evaluated the different N:K ratios (w/w) (1:0.5, 1:1.0, 1:2.0, and 1:3.0) in the reproductive growth phase, after a constant N:K 1:0.4 ratio during the vegetative growth stage of cucumbers. The results demonstrated that the ratios of 1:2.0 and 1:3.0 significantly improved yield and fruit size (Cardoso et al., 2018). Therefore, these results suggested that potassium concentration should be increased during the reproductive phase for cucumber production. In contrast, Macia et al. (1997) reported that a ratio of 3:1.0 reduced the marketable yield for peppers, whereas biomass accumulation in the vegetative parts of the plants were highly increased. Therefore, it is important to consider the nutrient formulation and the interrelationships of mineral elements in the solution with the growth stages of the crop during cultivation. For instance, low phosphorus (P), with high nitrate (NO_3^-) and sulphate (SO_4^{2-}) levels in the nutrient solution lowered calcium (Ca) uptake in tomatoes, whereas relatively high P and chlorine (Cl) levels increased Ca uptake in tomatoes cultivated in the NFT system (Yang and Kim, 2020). In addition, ratios for metallic macro elements, such as K:Ca:Mg or K:Ca, are important for the maintenance of the EC in the root zone, because excessively high Ca:K or Mg:K (magnesium: potassium) may result in ion build-up (Yang and Kim, 2020). Furthermore, the fluctuations of mineral contents in the nutrient solution are affected by the unbalanced anion and cation exchange reactions. Generally, these effects result in deficiencies of certain minerals, and will usually be visible on the leaves of the crop. Common deficiencies are Ca, which causes blossom end rot in tomatoes and peppers, Ion (Fe) which causes interveinal yellowing of the plant leaves, Mg which causes chlorosis on plant leaf edges, and nitrogen deficiencies retards plant growth and causes yellowing of the leaves (Yang and Kim, 2020). Therefore, for quicker recovery, foliar application by spraying of the nutrient solution onto the leaves should be considered. Another option is to flush the nutrient solution, and to refill and replenish nutrients in the reservoir (Cardoso et al., 2019).

Table 2.18: Nutrient formulations for lettuce as a leafy vegetable and tomato as a fruiting crop over the growing season (Çalişkan and Çalişkan, 2017).

Nutrient concentration (mg/L)	Lettuce	Tomato		
	Constant formulation up to harvesting	Weeks 0-6	Weeks 6-12	Week 12+
Nitrogen (N)	150	224	189	189
Phosphorus (P)	39	47	47	39
Potassium (K)	162	281	351	341
Calcium (Ca)	139	212	190	170
Magnesium (Mg)	47	65	60	48
Iron (Fe)	2.3	2.00	2.00	2.00
Manganese (Mn)	0.38	0.55	0.55	0.55
Zinc (Zn)	0.11	0.33	0.33	0.33
Boron (B)	0.38	0.28	0.28	0.28
Copper (Cu)	0.113	0.05	0.05	0.05
Molydenum (Mo)	0.075	0.05	0.05	0.05

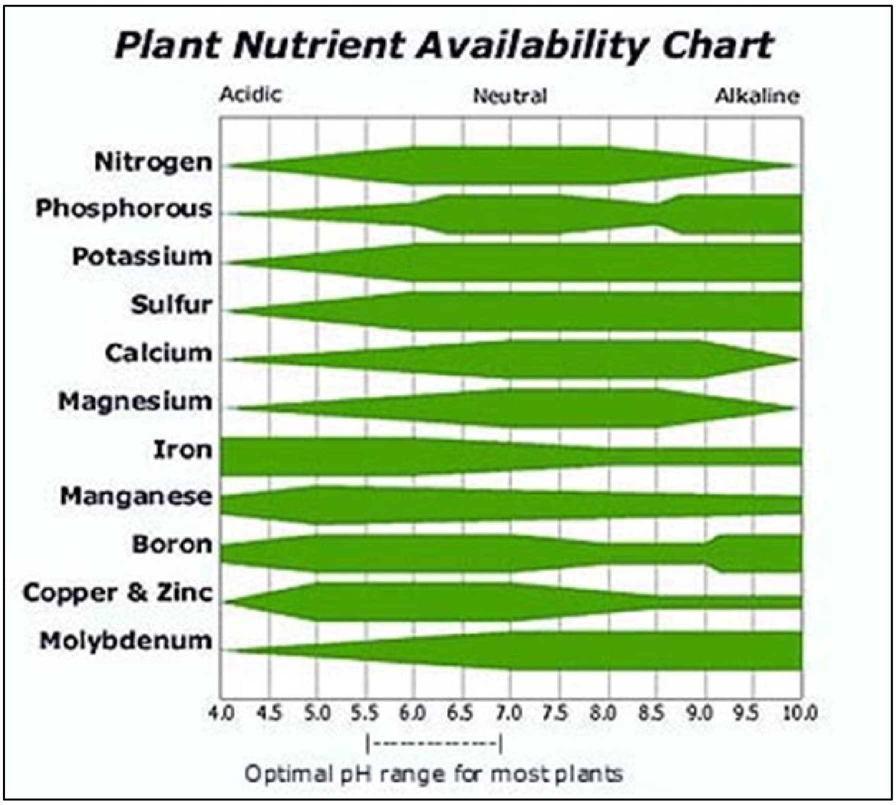

Figure 2.13: The ideal pH range of the elements in the hydroponic nutrient solution used for most of the crop plants (Sharma et al., 2018).

2.8.8 Application of growth-promoting rhizobacterial in the nutrient solution

Plant growth-promoting rhizobacteria (PGPR) are a combination of bacterial species that have positive effects on plant growth when inoculated into the plant rhizosphere. The relationship between crops and beneficial microorganisms has been known for many years in the context of soil-based agriculture. This is done through crop root colonization by microorganisms. It came with numerous advantages for crop productions, i.e. growth promotion, protection against pathogens, restoration of soil fertility and most importantly improvement of soil health. The benefits in the context of active recovery hydroponic systems are reported to be protection against infections and improved nutrient uptake (Pii et al., 2016). The recirculation of water and nutrients in active recovery hydroponics systems is vulnerable to uncontrollable pathogen spread, causing contamination during cultivation. The high levels of minerals in the nutrient solution, aggravates rapid pathogens growth and may cause up to 100% crop loss (Lee et al., 2016). Root rot is the most common problematic disease caused by fungi, oomycete and bacteria (Lee et al., 2016). Therefore, the use of chemicals such as Calcium Hypochlorite and Chlorine dioxide were used to prevent these infections (Lee et al., 2016). However, since the use of chemicals is highly discouraged by organic markets and consumers, it is important to consider organic alternatives for prevention of infections and increased bioavailability of mineral nutrients in the crop rhizosphere. For this purpose, the use of PGPR has been well documented in soil-based farming, whereas in soilless-based hydroponics is still gaining popularity (Mia et al., 2010; Pii et al., 2018). Hence, there now more studies highlighting the positive effects of PGPR on active recovery systems (Mia et al., 2010; Pii et al., 2018). For instance, *Pseudomonas chlororaphis* has been reported to have protected tomatoes from root rot in closed hydroponics caused by *Fusarium oxysporium* (Pii et al., 2016). *P. chlororaphis* treatment was also reported to have significantly promoted lettuce growth and yield by influencing root hair and number of leaves grown in NFT hydroponic system (Figure 2.13) (Lee et al., 2016). The reports are mostly in relation to growth promoting effects due to the ability to enhance nutrient uptake. Moreover, Pii et al. (2018) reported that PGPR inoculated strawberry plants resulted in increased fruit size and it was speculated that *Azospirillum brasilense* also influenced allocation of nutrients in fruits grown under NFT hydroponic system. Pii et al. (2018) further indicated the significant increase in the concentration of antioxidant compounds such as flavonoids which are important for human health. However, it is important to note that the effects of beneficial microorganisms in soil-based farming and recirculation hydroponic farming could be contradictory. Maboko et al. (2013) evaluated the use of Abiscular Mycorrhizae inoculation using sawdust as medium and the results demonstrated no effects on growth and yield of tomato plants grown in GFT hydroponic system. Moreover, the use of effective microorganism (EM) (a highly reputable commercial soil-based bio-fertilizer) has shown no effects on strawberries grown in the NFT system (Pii et al., 2018). Therefore, most authors agree that the effects of these PGPR are dependent on growth mediums and cultivar selection (Maboko et al., 2013; Pii et al., 2018).

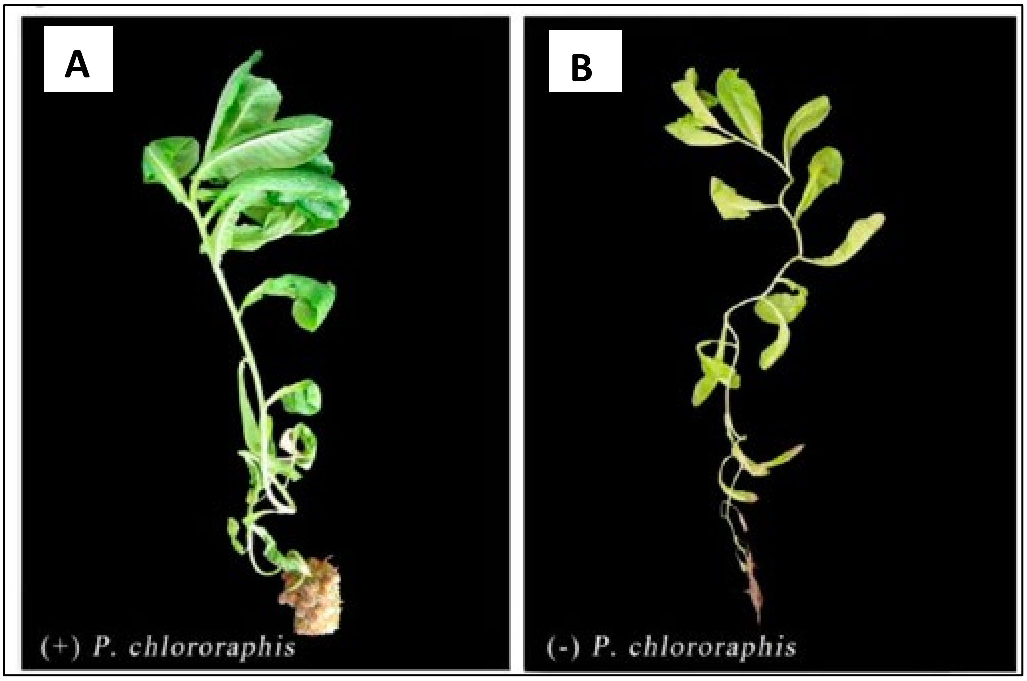

Figure 2.14: Effects of Pseudomonas chlororaphis-treated lettuce (A) root with clay and non-Pseudomonas. chlororaphis treated lettuce (B) root (Lee at al., 2016).

2.9 Case studies on performance of commonly grown food crops under active, recovery hydroponic systems

Active recovery hydroponic systems have been used to grow a variety of crops, including leafy, fruiting, dual-purpose vegetables and herbs. Lettuce is the most commonly grown leafy vegetable on these systems, and it is mainly produced under the horizontal and vertical NFT pipe systems, as well as the GFT system (Genuncio et al., 2012; Chiloane, 2012; Maboko and Du Plooy, 2013; Heredia, 2014; Sace and Estigoy, 2015; Touliatos et al., 2016; Fraile-Robayo et al., 2017; Mampholo et al., 2017; Singh, 2017; Goddek and Vermeulen, 2018). Other crops that have also received attention by researchers in active recovery systems are sweet basil, tomato and strawberry. Sweet basil herb crop is mainly produced under the NFT pipe system (Olfati et al., 2012; Maboko and Du Plooy, 2013; Walters, 2015; Singh, 2017; Wilson, 2017; Walters and Currey, 2019). While tomato has been mostly cultivated under the GFT system (Field, 2002; Maboko et al., 2011; Maboko and Du Plooy, 2013; Maboko et al., 2017). Strawberry is commonly cultivated in vertical NFT pipe and vertical bucket columns systems

(Peralbo et al., 2005; İncemehmetoğlu, 2012; Ramírez-Gómez et al., 2012; Treftz and Omaye, 2015; Ramírez-Arias et al., 2018). Other crops that were less studied but reported to have performed well in active recovery hydroponic systems, include green onions (Thompson et al., 2005; Kane et al., 2006), celery (Li et al., 2010) and Swiss chard (Maboko and Du Plooy, 2013).

2.9.1 Lettuce

The performance of lettuce (*Lactuca sativa* L.) on active recovery systems has been studied in detail in terms of growth, physiology, yield and quality of the crop, as affected by several management practices. This included testing concentrations, flow rates and pH buffers of the nutrient solution, plant spacing, variety type and growing seasons (Genuncio et al., 2012; Chiloane, 2012; Maboko and Du Plooy, 2013; Heredia, 2014; Sace and Estigoy, 2015; Touliatos et al., 2016; Chidiac, 2017; Fraile-Robayo et al., 2017; Mampholo et al., 2017; Singh, 2017; Goddek and Vermeulen, 2018). However, most of the research has been conducted under horizontal cultivation, and only few studies have reported the performance of this crop under vertical farming using the NFT pipe system (Heredia, 2014; Sace and Estigoy, 2015; Touliatos et al., 2016). Studies on vertical cultivation of lettuce focused on assessing system's performance when compared to conventional cultivation, as well as crop response to different growing medium. (Table 2.19) illustrates the range of fresh weight yield values of lettuce obtained under different crop management scenarios, for the horizontal cultivation with GFT and NFT pipe systems, as well as vertical cultivation with the NFT pipe system. In general, lettuce yield per plant is lower in vertical cultivation systems when compared to horizontal cultivation, but the total yield per growing floor may be higher in the former considering that higher number of plants can be cultivated. However, from the current research results that are available, the potential of vertical farming systems is still not clear when compared to horizontal systems, as illustrated in (Table 2.19). Therefore, further research should be conducted to compare the performance of various crops across different active recovery systems with horizontal versus vertical cultivation set-ups. Also, there is a need to identify optimum planting densities, plant arrangement configurations, concentration and flow rates of the nutrient solution, as well as the type of hydroponic structure (High tunnel vs shade net) for vertical farming systems.

Table 2.19: Leaf fresh mass yield of different types of lettuce grown under various active recovery systems namely, the gravel film technique (GFT), the nutrient film technique (NFT) with horizontal and vertical cultivation.

		GFT		
Lettuce type	Planting density (Plants m^{-2} growing floor)	Growing length (days)	Leaf fresh mass (g $plant^{-1}$)	Reference
Loose leaf	50	28	58.1-119.0	Maboko and Du Plooy (2013
Loose leaf	25	30	34.4-210.9	Mampholo et al. (2017)
Loose leaf	33	30	163.4-235.2	Chiloane (2012)
		Horizontal NFT pipe		
Lettuce type	Planting density (Plants m^{-2} growing floor)	Growing length (days)	Leaf fresh mass (g $plant^{-1}$)	Reference
Butterhead	17	45	59.5-163.7	Genuncio et al. (2012)
Butterhead	12	49	239.1-334.6	Goddek and Vermeulen (2018)
Romaine	50	70	138.0	Touliatos et al. (2016)
		Vertical NFT pipe		
	Planting density (Plants m^{-2} growing floor)	Growing length (days)	Leaf fresh mass (g $plant^{-1}$)	Reference
Loose leaf	49	30	46.4-50.0	Sace and Estigoy (2015)
Romaine	1000	70	95.0	Touliatos et al. (2016)

2.9.2 Sweet basil

Sweet basil (*Ocimum basilicum* L.) is another crop that has received attention of researcher in the field of active recovery hydroponic systems. Research studies on this crop included assessment of crop performance in terms of growth, yield, plant quality and nutrition under various production systems (Walters, 2015; Wilson, 2017), concentrations of the nutrient solution (Olfati et al., 2012; Walters, 2015), types of cultivar (Walters and Currey, 2019), planting densities (Maboko and Du Plooy, 2013) and pH buffers (Singh, 2017). Most of these studies were conducted under horizontal NFT pipe systems, except the one conducted by Maboko and Du Plooy (2013) which was under the GFT system. (Table 2.20) illustrates the range of fresh weight yield values of sweet basil obtained under different crop management scenarios. Similarly, to lettuce, there is a need for further research on sweet basil, particularly under the vertical farming system, since there is no information available currently. Sweet basil seem to respond well to increased planting densities, as maximum yields were observed at the highest planting densities tested (Maboko and Du Plooy, 2013; Walters and Currey, 2019). Future research can consider investigating the effect of higher planting densities (above 50 plants/m^2 of growing floor) on crop productivity of sweet basil. Planting arrangement/ pattern is also an aspect that needs to be investigated, especially in vertical farming systems, in order to optimize light/radiation use efficiency and productivity of the crop. In addition, cultivar choice also affects the yield, with large leaf cultivars having considerably higher yields than the narrow leaf ones (Walters and Currey, 2019).

Table 2.20: Leaf fresh mass yield of sweet basil grown under different active recovery systems namely, the gravel film technique (GFT) and the nutrient film technique (NFT) with horizontal cultivation.

Planting density (Plants m^{-2} growing floor)	Growing length (days)	Leaf fresh mass (g plant^{-1})	Reference
		GFT system	
40	30	86.8-87.0	Maboko and Du Plooy (2013)
		Horizontal NFT pipe system	
50	21	15.0-50.6	Walters and Currey (2019)

2.9.3 Tomato

Research on tomato (*Lycopersicon esculentum* Mill.) grown under the active recovery systems has focused on crop yield responses to pruning, fruit thinning and plant spacing (Field, 2002; Maboko and Du Plooy, 2013; Maboko et al., 2017) and cultivar selection (Maboko et al., 2011). Most of this research was conducted under the GFT system, except the work by Field (2002) which was conducted under the NFT channel system. This is mainly attributed to the morphological characteristics of the crop, which has high fruit load and branching stems with a terminal bud at the tip or *apex* that is responsible for the increase in length of the main stem. As a result, the crop requires trellising to keep it upright for continuous growth. In addition, the crop has a long growing length of at least five months, making it less appropriate for NFT systems. (Table 2.21) illustrates the range of fresh weight yield values of tomato obtained under different crop management scenarios. Based on these findings, the marketable yield of tomato is highly influenced by the type of tomato fruit and cultivar, as well as planting densities. Fresh market tomatoes generally have higher yields compared to cherry tomatoes. Similarly, cultivars of indeterminate growth have higher potential for increased yields as compared to determinate ones. High tomato yields, under the NFT channel system with horizontal cultivation, are possible for both cherry and fresh market tomatoes. However, the GFT system is more likely to produce higher yields, particularly if the correct planting density is used. Other factors contributing to high yields include selection of the right cultivar and crop manipulation such as removal of the growing point and limiting of flower trusses (Maboko and Du Plooy, 2013).

Table 2.21: Marketable yield of tomato grown under different active recovery systems namely, the gravel film technique (GFT) and the nutrient film technique (NFT) with horizontal cultivation.

Tomato type	Planting density (Plants m^{-2} growing floor)	Growing length (days)	Marketable yield (g $plant^{-1}$)	Reference
GFT system				
Fresh market – indeterminate growth	2.5	180	5700-7608	Maboko et al. (2011)
Fresh market – determinate growth	25	180	610-835	Maboko and Du Plooy (2013)
Fresh market – indeterminate growth	25	180	589-1080	Maboko and Du Plooy (2013)
Fresh market – indeterminate growth	25	180	932-967	Maboko et al. (2017)
Horizontal NFT pipe system				
Cherry – indeterminate growth	2.76	240	2104	Field (2002)
Fresh market – indeterminate growth	2.76	240	2962-4834	Field (2002)

2.9.4 Strawberry

Strawberry may be a good potential crop for growth in hydroponic systems. Treftz and Omaye (2015) tested strawberry production in a recirculating hydroponic system compared to conventional soil cultivation. They concluded that, strawberry production in hydroponic systems is feasible, at reasonable cost and more sustainable compared to traditionally soil grown systems. The potential for growing strawberry in recirculating hydroponic systems has also been confirmed by Peralbo et al. (2005) in a separate study. Ramírez-Gómez et al. (2012) investigated the performance of strawberry under four different hydroponic system set-ups: (a) open bag system; (b) vertical nutrient film technique with three layers; (c) vertical nutrient film technique with four layers and (d) vertical bucket columns system (Figure 2.14).

Figure 2.15: Comparison of hydroponic systems in strawberry production: (a) open bag system; (b) vertical nutrient film technique with three layers; (c) vertical nutrient film technique with four layers and (d) vertical bucket columns system (Ramírez-Gómez et al., 2012).

Based on the above-mentioned study results, plants growing at the upper levels of the vertical NFT pipe system received better photosynthetic irradiance, which resulted in higher substrate temperature and consequently higher °Brix, as compared to plants at the lower levels of the system. However, the highest most significant cumulative yield per plant was obtained under the vertical bucket columns system (4595 g m^{-2}) and vertical NFT pipe system with four levels (3961 g m^{-2}). Whereas the vertical NFT pipe system with three levels produced significantly lower yield than the first two systems (2755 g m^{-2}), but significantly higher than the open bag system (856 g m^{-2}). A similar study conducted by Ramírez-Arias et al. (2018) confirmed the above-mentioned findings. There were no significant differences between the vertical bucket columns and vertical NFT pipe systems in terms of yield per plant (202.3-230.7 g $plant^{-1}$). But the total yield per growing floor was significantly higher using the vertical bucket columns system (11330 g m^{-2}) when compared to the vertical NFT pipe with five layers (6074 g m^{-2}) and the vertical NFT with three layers (3561 g m^{-2}). This is explained by higher planting density with the vertical bucket columns (49.1 plants m^{-2}) when compared to the vertical NFT with five (29.5 plants m^{-2}) and three layers (17.7 plants m^{-2}). (Table 2.22) summarizes research findings reported on different studies, which were conducted on strawberry production under active recovery systems. From these studies, it is clear that strawberry yield per growing floor area increases with increased layers of vertical NFT pipe systems. However, studies testing different plant arrangements or configurations in vertical NFT pipe systems are still lacking. These studies will be relevant in future to improve light/radiation use efficiency of the crop for maximum crop productivity. In addition, further investigation is required to identify optimum growing medium, concentration, and flow rates in vertical NFT systems for strawberry production.

Table 2.22: Strawberry yield grown under different active recovery systems namely, the vertical bucket columns system and the vertical nutrient film technique (NFT) pipe system with three, four and five layers.

Planting density (Plants m^{-2} growing floor)	Growing length (days)	Cumulative yield (g $plant^{-1}$)	Cumulative yield (g m^{-2})	Reference
Horizontal nutrient film technique				
11	240	379-505	4170-5560	Peralbo et al. (2005)
Vertical bucket columns				
Not known	180	Not known	4595	Ramírez-Gómez et al. (2012)
40.10	240	231	11330	Ramírez-Arias et al. (2018)
Vertical nutrient film technique with three pipe layers				
Not known	180	Not known	2755	Ramírez-Gómez et al. (2012)
17.67	240	202	3561	Ramírez-Arias et al. (2018)
Vertical nutrient film technique with four pipe layers				
Not known	180	Not known	3961	Ramírez-Gómez et al.(2012)
Vertical nutrient film technique with five pipe layers				
29.56	240	207	6074	Ramírez-Arias et al. (2018)

2.10 Conclusions and recommendations

Active recovery or recirculating hydroponic systems are gaining increasing popularity, not only in South Africa but also in other parts of the world. The most commonly implemented systems are the horizontal nutrient film technique (NFT), the ebb-and-flow and the gravel film technique (GFT). These systems often operate under shade nets, which is the most popular type of structure used for hydroponics production particularly in South Africa, followed by non-temperature-controlled tunnels. The NFT system operating under shade nets is generally used for growing leafy vegetables, with lettuce being the most dominant crop, while the same system operating in non-temperature-controlled tunnels and greenhouses is often used for growing fruiting crops with strawberry being the most dominant one. The ebb-and-flow technique is mainly practiced to grow commercial fruiting vegetables like tomato, cucumber and pepper. The GFT system on the other hand, is well suitable for growing both, leafy and fruiting vegetables. Research on vertical NFT systems under both, controlled and non-controlled environmental conditions is still very limited, despite the noticeable potential of these systems for increased land, water and nutrient use efficiencies in crop production. Therefore, these is a need to conduct more research on these systems to develop optimum cultivation practices for a range of potential crops such as lettuce, basil and strawberry, as well as to optimize hydroponic systems operational parameters, including water flow rates and concentrations of the nutrient solution.

To date, there are no studies that have shown thresholds of electrical conductivity (EC) levels of the recirculating nutrient solution, when refilling is absolutely needed. This knowledge generation is relevant in active recovery systems since the frequency of refill solution is determined by the ratio of solution volume to plant growth rate. In addition, the tolerance of nutrient imbalance in the solution may be a crop-specific factor, as some crops can have higher ability than other crops, to store the nutrients that were rapidly absorbed from the solution in roots, stems or leaves, and remobilize them as needed. Similarly, there is a need to adjust flow rates of the nutrient solution in NFT systems, not only for specific crops but also for specific crop management practices. For example, higher planting densities may result in slower flow rates due to denser volume of roots within the NFT pipes.

Crop management aspects such as planting density, cultivar selection, pruning and suitable growing media identification are well documented for active recovery systems, particularly for those with horizontal cultivation. On the contrary, scientific information on management strategies, such as harvesting frequency, planting frequency and plant spatial arrangements, are still limited in the literature. These aspects are important to add value and optimally reap the benefits of cultivation under the active recovery systems. For instance, farmers are generally interested on both planting and harvesting frequency in order to respond to market demands and volatility. Also, harvesting methods and frequencies vary according to a specific crop. Generally, fruiting crops have shorter harvesting frequency, whereas leafy vegetables take longer. Therefore, studies should be done to address shortages of information in vertical farming. Management of fruiting crops include pruning, trellising and training which are seldom studied scientifically. Information on these topics is usually documented in non-scientific platforms, which often makes it inaccurate and unreliable. Hence, it is highly recommended that scientific studies of this nature be done in order to expand knowledge on these crop management aspects.

Although lettuce, sweet basil, tomato and strawberry have been the most studied and documented crops in active recovery hydroponics systems, there are still gaps in knowledge particularly under vertical hydroponic systems. There is a need to conduct a thorough assessment of advantages and disadvantages of horizontal versus vertical NFT systems implemented under varying crop management practices, especially planting densities/arrangements/patterns to optimize light/radiation use efficiency by the crop, root nutrient and water uptake, as well as a cost-benefit analysis of their implementation. Information on water usage/utilization across varying active recovery systems is almost completely inexistent. Thus, there is an absolute need to determine how much water these systems use per life cycle of a growing crop. A quantification of the number of inorganic fertilizers used is also necessary, since these systems operate on the basis of a recirculation of the nutrient solution, making them very likely to be water- and nutrient-use efficient. Such knowledge generation is necessary to promote the utilization of these systems in crop production and to influence policy decision-makers towards a positive perception and attitude on the use of recirculating hydroponic systems for crop production. This is of utmost importance in a water-scarce country like South Africa, where there are limited water allocations to growers, in spite of the growing demand for food production.

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CHAPTER 3: SITUATIONAL ANALYSIS ON THE CHARACTERISTICS OF HYDROPONIC FARMERS, THE STATE OF HYDROPONICS AND URBAN FARMING IN THE GAUTENG PROVINCE

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3.1 Introduction and background information

Gauteng Province is situated in northeastern South Africa. It consists of the cities of Pretoria, Johannesburg, Germiston, and Vereeniging and their surrounding metropolitan areas in the eastern part of the Witwatersrand region. Gauteng is the smallest South African province. It is bordered by the provinces of Limpopo on the north, Mpumalanga on the east, Free State on the south, and Northwest on the west. Until 1994 Gauteng (called Pretoria-Witwatersrand-Vereeniging in 1994-95) was part of the former Transvaal province. The provincial capital is Johannesburg.

Demographically and economically, Gauteng is the major province of South Africa. It contains around 18% of the country's population and is mainly urban in nature. 99.6% of the province's residents are city dwellers, one third of whom live in the City of Johannesburg Metropolitan Municipality, which represents only 6.4% of the surface area of the province. Local governance in the province is carried out via three Metropolitan Municipalities and two District Municipalities, with these District Municipalities further broken down into three and four local municipalities respectively. These municipalities are further broken down into 130 wards that cover the province

.

To obtain a more complete overview of the experiences, challenges and aspirations of hydroponic smallholder farmers in Gauteng Province, the present study conducted a detailed situational analysis to provide a comprehensive characterization of their current practices in a range of systems including open-bag hydroponics across different growing regions. The study further presents an analysis of the state of food security in Gauteng Province in terms of land, water, food and energy resources. It also describes how hydroponic production systems can play a role in the production of food to increase food security in the province without substantially increasing the amount of land, water and energy required to feed an ever-increasing population within urban areas.

3.1.1 Problem statement

Hydroponic crop production systems require high initial investment to set-up the infrastructure, skilled personnel for system operation and management, increased energy consumption to operate the systems and high fertilizer inputs, since these systems function in soilless cultures that require continuous nutrient supply. Hence, farmers are often pressured to deliver quick return on investments in order to make crop production more profitable and sustainable. Rapid and high return on investments can be achieved through better system management and improved market access. In order to achieve this, it is important to assess and characterize the current practices followed by farmers so as to identify areas that need to be prioritized for intervention.

3.1.2 Study aim and objectives

The present situational analysis study aimed to provide a broad set of information related to hydroponic farmers' crop production and market access, which would inform the alignment of subsequent project activities. It also provides an overview of the state of hydroponics and urban farming in Gauteng Province. Given this context, nine primary objectives were formulated in this situational analysis study, as follows:

- To provide an overview of hydroponic farmers' farming characteristics in Gauteng Province of South Africa;
- To gain a better understanding of the available fresh produce markets, or commercial small-scale farmers;
- To characterize risks to smallholder farmers' fresh produce due to weather conditions across Gauteng Province;
- To identify potential risk mitigating mechanisms for smallholder farmers;
- To map-out the supply chain and distribution channels for smallholder fresh produce;
- To identify potential value-adding technologies for smallholder farmers fresh produce;
- To investigate the process of fresh produce contract farming with formal markets.
- To analyze the population dynamics, food security, employment, land use, water and energy resources in Gauteng Province, and
- To evaluate the potential of hydroponic production systems as an alternative option to enhance household food security.

3.2 Research methodology

This study made use of both primary and secondary data for the situational analysis research. Original data were collected by interviewing representatives from the two biggest rooftop farming organizations in Gauteng – Johannesburg inner city, as well as two of their rooftop farmers. The current situation created by the Covid-19 pandemic has been largely excluded from this report. For instance, the impact of Covid-19 on the functioning of hydroponic rooftop farms has been excluded. The following sub-sections provide brief methodology descriptions on how these data sources were acquired and used in the study.

3.2.1 Primary data sources

Two detailed structured questionnaires were developed in English for the data collection on hydroponic farmers' characteristics (first questionnaire developed for farmers) and market understanding (second questionnaire developed for market agents). Where translation to a different language was needed, it was achieved with the aid of a researcher or a participant's family member. Site observations were conducted where possible; otherwise, the interviews were handled telephonically or via e-mail. Both questionnaires included open and closed ended questions and a section requesting for participant consent to be interviewed, with a clear indication that all responses given would be used for research purposes only. The sample size for the study on farmers' characteristics comprised of 13 commercial hydroponic farmers from different regions (western, eastern and Tshwane) of Gauteng Province. These farmers were extracted from databases provided by the Gauteng Department of Agriculture, Rural Development and Environment (GDARDE) and Agricultural Research Council (ARC), to include those farmers who were actively involved in hydroponic production at least for the past 3-5 years, with the main farming purpose being generation of income and profit. A 100% response rate was received from these farmers. For the study on market understanding, the City of Tshwane market (Figure 3.1), which is located in Pretoria, was selected to represent national fresh produce formal markets. This selection was based on the fact that the Tshwane market is one of the largest markets in South Africa, with approximately half the turnover and tonnage of the Johannesburg fresh produce market. In addition, the Tshwane market, like other national formal markets, allows for equal trade opportunities for large scale, commercialized producers and smallholder farmers producing small quantities of produce, without discrimination based on volume or origin of fresh produce (Chikazunga et al., 2008). The questionnaires were sent out to all identified agents in the Tshwane market (11 in total) and a 55% response rate was obtained. Descriptive analyses were conducted using simple statistical parameters such as averages, maximum and minimum values, with statistical results being represented by percentages.

Figure 3.1: The City of Tshwane market located in Pretoria, Gauteng Province of South Africa (https://www.freshplaza.com/article/2172011/tshwane-market-south-africa-s-second-largest/).

3.2.2 Secondary data sources

Secondary information for the situational analysis study was obtained from published peer-reviewed papers, research and development reports, institutional reports (research and development, including NGOs), academic theses, government agricultural reports, web-based data sources and national census publications.

3.3 Farmers' socio-economic characteristics

3.3.1 Demography

Most non-subsistence farmers who participated in this situational analysis study were female (71%) and located in the western region of Gauteng (85%). All interviewed farmers were black South African citizens (Table 3.1) and emerging commercial farmers in terms of production scale, who were mainly dependent on the state and semi-state organizations for support and finance. In general, all aspired to farm successfully within their given physical, mental and socio-economic constraints and reliance on assistance from external facilitators to realize this aspiration. There were two distinct groups of farmers: (1) middle age – 26 to 35 years old and (2) old age – above 45 years old. Expectedly, the majority of these farmers (57%) had tertiary education, which gives them an advantage to manage hydroponic systems more effectively, by making more appropriate choices of production practices that are profitable and environmentally sound. For example, 75% of the participants responded that they conducted chemical analysis of the water source used for crop production because they were aware of the presence of certain mineral elements or impurities in the water that could be harmful to plant and human health (examples include heavy metals and microorganisms). In addition, 63% of the respondents indicated having access to weather information, either through the South African Weather Service, electronic media or own sensors installed on the farm (particularly rain gauge and temperature monitoring tools).

Table 3.1: Demographic characteristics of the interviewed commercial farmers.

Demographic characteristic	
Gender	71% female, 29% male farmers
Race and citizenship	100% Black South Africans
Education level	57% with tertiary, 29% with secondary and 14% with primary level
Non-subsistence farmer's production scale	100% emerging commercial farmers

3.3.2 Farming experience

The majority (57%) of the interviewed farmers farmed on their own land, while the remaining 47% leased government land. The total number of years in farming experience varied from a minimum of 3 years to a maximum of 30 years. This experience was partly in hydroponics and conventional soil-based crop production. Most of the farmers (88%) began farming in conventional soil systems, and only recently (within the past 3 to 5 years) embarked on hydroponics with the aid of external funders in most cases (mainly the Gauteng Department of Agriculture, Rural Development and Environment (GDARDE), the Department of Agriculture, Land Reform and Rural Development (DALRRD) and non-governmental organizations (NGOs) such as South African Breweries Ltd (SAB). These external funders provide farmers with hydroponic systems infrastructure (mostly non-temperature-controlled plastic tunnels and multi-span structures), initial production inputs (fertilizers, seeds/seedlings) as well as training on how to operate and manage the systems. Given their relevant knowledge and experience, all interviewed farmers responded that they managed the farms by themselves, with assistance of neighboring farmers who had more experience in crop production and/or extension officers provided by external funders. Most respondents (90%) indicated that these extension officers visited them at least once a month during the project implementation period to provide training and monitoring of farmers’ practices in terms of production systems and management, market information, new technologies amongst other aspects.

3.3.3 Farm enterprises and enterprise productivity

Hydroponic farmers included in the survey generally had large arable land (as large as 17 hectares) available for crop production. However, most of this land was either bare without any agricultural activities (40-60%) or conventionally cultivated (31-58%) with crops like leafy vegetables (kale, lettuce, spinach and cabbage), fruity vegetables (cucumbers and peppers under a shade net protection) as well as legumes like green beans. Only half of the respondents had shade nets (one or two per farmer), as indicated in (Table 3.2). The land occupied by hydroponic production systems was as small as 2-9% of their total land size. Farmers did not have full climate-controlled greenhouses. The majority (87%) had non-temperature-controlled tunnels (standard 300 m^2 structures – 88% of these farmers and multi-span structures of 51x32 m in size – 12% of these farmers), while the remaining 13% of interviewees had temperature-controlled structures by means of a fan system. Half of the total number of interviewed farmers d having shade net structures as well (various sizes, from 300 to 2160 m^2). Surprisingly, only a small minority of the interviewed farmers (13%) had an existent recirculating hydroponic system.

Table 3.2: Respondent distribution based on the existent number and type of hydroponic structures.

Hydroponic structure	% of farmers based on the number of hydroponic structures available					
	0	1 to 2	3 to 6	7 to 10	10 to 15	≥ 15
Non-temperature-controlled plastic tunnel	13	25	23	13	13	13
Temperature-controlled plastic multispan tunnel	87	13	0	0	0	0
Shade net	50	50	0	0	0	0

The percentage of farmers decreased with increased number of available non-temperature-controlled plastic structures (Table 3.2), demonstrating that only a small group of farmers have the capacity to produce fruity crops at a larger scale in order to meet market demands or secure formal market contracts. It was also interesting to note that hydroponics production was often conducted under plastic tunnels or multi-span structures, while soil cultivation was often conducted in both plastic tunnels and shade nets. This is most likely due to relatively cool weather conditions in the Gauteng Province, where monthly maximum and minimum air temperatures fluctuate from 26.10-26.73°C and 11.13-14.60°C in the eastern region, 28.44-30.52°C and 11.01-15.51°C in the western region, and 28.23-29.60°C and 13.16-16.15°C in the Tshwane region, respectively. Due to such weather conditions, farmers are pressured to produce in plastic structures to create more optimal conditions for crop growth, accelerate growth rate of the plants and increase chances of continuous production, market supply and income generation throughout the year. (Figure 3.2) shows lettuce production under a temperature-controlled plastic structure (operated by AB Farms – two young farmers, from 2016 to 2019 at AgriPark, Westonaria, which was thereafter discontinued due to poor crop marketable quality, limited market access and low profitability). (Figures 3.2, 3.3 and 3.4) illustrate tomato and pepper production in hydroponics under non-temperature-controlled plastic structures in the Gauteng Province of South Africa.

Figure 3.2: Lettuce production in hydroponics using a large nutrient film technique recirculating system under a temperature-controlled plastic tunnel at AgriPark, Westonaria, Western region of Gauteng Province (Picture taken by Mr Silence Chiloane, 2019).

Figure 3.3: Tomato production in hydroponics under a non-temperature-controlled plastic tunnel at Tombisa Farming, Cullinan, Tshwane region of Gauteng Province (Picture taken by Mr Silence Chiloane, 2019).

Figure 3.4: Tomato (a) and pepper (b) production in hydroponics under a non-temperature-controlled plastic tunnel at Robela Farming, West Rand, Western region of Gauteng Province (Picture taken by Ms Maria Robela, 2021).

Figure 3.5: Tomato production in hydroponics under a non-temperature-controlled plastic multi-span at TC Women in Action Farm, West Rand, Western region of Gauteng Province (Picture taken by Ms Patricia Phasha – 2021).

In between tunnels or multi-span hydroponic structures, farmers produce a variety of vegetables in soil (Figure 3.6). When hydroponics does not become a profitable business, due to high costs of fertilizers and growing media amongst other inputs that are required, farmers tend to produce their crops directly in soils under protection using tunnels and shade nets that were previously set-up for hydroponic production (Figures 3.6 and 3.7). Crops grown under protection are safe from harsh environmental conditions like hail, frost, strong winds and heavy rainfall. In addition, there is often increased water use efficiency, excellent quality of harvestable fresh produce, minimum to no incidence of pests, higher crop productivity, reduced input costs due to a more efficient utilization of fertilizers and low labour requirements to manage farm operations like weeding (Nguyen et al., 2016; Johnson et al., 2017). When there is lack of knowledge and skills to operate the systems, farmers tend to abandon hydroponics completely, shifting from cultivating crops of indeterminate growth to those of determinate growth under open field conditions, which the case is shown in (Figure 3.6). Farmers also tend to expand their production through conventional cultivation, which requires fewer inputs. But in doing so, they often comprise the quality of the marketable fresh produce, with consequent negative impact on market access, income generation and profitability.

Figure 3.6: Swiss chard production in soil under open field conditions, in between multi-span structures at TC Women in Action Farm, West Rand, Western region of Gauteng Province (Picture taken by Ms Patricia Phasha – 2021).

Figure 3.7: Cucumber production in soil under a non-temperature-controlled plastic tunnel structure at Tombisa Farming, Cullinan, Tshwane region of Gauteng Province (Picture taken by Mr Gino Tombisa – 2021).

Figure 3.8: Pepper production in soil under a non-temperature-controlled plastic tunnel structure at Mr Ntlhalefeng Letsholo's Farm, West Rand, Western region of Gauteng Province (Picture taken by Mr Letsholo – 2021).

Figure 3.9: Brinjal production in soil under open field conditions at Mbatha Fruit and Vegetables Farm, Zuurbekom, Western region of Gauteng Province (Picture taken by Mrs Nomasonto Mbatha – 2021).

Table 3.3 indicates crop productivity per unit area planted for various crops under different production systems. The most cultivated crops were lettuce and spinach in open field, cucumbers and peppers in soil under shade net or tunnel protection, cucumbers, peppers and tomatoes in hydroponics under non-temperature-controlled plastic structures and lettuce in the vertical nutrient film hydroponic technique. Conventional soil cultivation under the open field conditions was primarily employed for cultivation of leafy vegetables (lettuce and spinach), because these usually have lower thermal time requirements for crop growth and development. Fruity vegetables on the other hand, were primarily produced under protection in soil or soilless cultivation. This is probably because they are relatively tall, making them more susceptible to wind damage, and they require higher thermal time accumulation to achieve optimum productivity when compared to leafy crops. It was interesting to note that crop productivity increased considerably from conventional soil production to hydroponic production under plastic structures. However, the yields obtained by farmers for those crops were still much lower (40-60%) than their potential yields.

Table 3.3: Average marketable yield across the study sample per unit of area planted for various crops under different production systems – a comparative evaluation assessment.

Crop type	Type of production system	Number of plants per m^2	Farmers' actual crop yield	Potential crop yield
Butterhead lettuce	Soil production under open field	16	13 heads (80-100 g/plant) per m^2 every six weeks	13 heads (143.4 g/plant) per m^2 every six weeks[1]
Spinach		8	0.4 kg per m^2 every four weeks	0.6 kg per m^2 every four weeks[2]
English cucumber	Soil production under a shade net	2	0.6 kg per m^2 every week	-
Green pepper		2	0.4 kg per m^2 every 2nd week	-
English cucumber	Soil production under a non-temperature-controlled plastic structure	2.5	1 kg per m^2 every week	1.7 kg per m^2 every week[6]
Green pepper		2.5	0.75 kg per m^2 every 2nd week	-
Leafy lettuce	Large vertical nutrient film technique under plastic structure	150	130 heads (30 g/plant)per m^2 every two weeks	130 heads (50 g/plant) per m^2 every two weeks[3]
English cucumber	Hydroponics under a non-temperature-controlled plastic structure	2.5	2 kg per m^2 every three days	-
Green pepper		2.5	0.5.0 kg per m^2 every 2nd week	1.2 kg per m^2 every 2nd week[4]
Tomato		2.5	0.60 kg per m^2 every week	1.0 kg per m^2 every week[5]

1 – Yosoff et al., 2015; 2 – Araya et al., 2021; 3 – Sace and Estigoy (2015); 4 – Maboko and Du Plooy (2015); 5 – Chiloane (2019); 6 – Farag et al. (2010); – no information found in the literature.

3.3.4 Farmers' knowledge and farming practices on hydroponics production

The interviewed farmers had some knowledge of hydroponics production operations, particularly on fruity crops (such as tomato, pepper and cucumber) produced in an open-bag system using sawdust as the growing medium. They were aware of the need for pruning and trellising of indeterminate growth crops for improved plant growth and development. However, only 25% of farmers practiced fertigation scheduling according to crop type and growth stage specific requirements indicated in Table 3.4. These farmers fertigated younger plants (first 8 weeks after transplanting) more often compared to older plants but kept the duration of each watering cycle constant throughout the growing season, leading to higher fertigation application when the plants were relatively small. Consequently, it was most likely that the plants were overirrigated during those periods, due to the presence of small plant root and canopy systems. Levels of electrical conductivity (EC) and pH of the nutrient solution were generally kept constant for all crops. Electrical conductivity, as a measure of soluble salts in the nutrient solution, should be adjusted according to crop nutrient requirements during the growth season. Failure to do so may result in either poor root water uptake by the plant if the EC is too high or insufficient plant nutrition if the EC is too low. Both cases are detrimental to crop growth and development, as they can result in the development of physiological and ultimately pathological disorders, leading to low crop productivity, poor income generation and less sustainable livelihood. In addition, farmers were not aware of potential salt built-up into the open-bag system, if a 5-10% additional irrigation is not accounted for. They also could not indicate the dripper delivery rate, making it difficult to assess how much water hydroponics farmers normally supply to their crops under the various systems utilized for production.

Table 3.4: Farmers' practices of fertigation scheduling, electrical conductivity and pH adjustment of the nutrient solution in an open-bag hydroponic system.

Crop	**No of cycles per day**		**Frequency and Duration of each cycle**		**EC level (dS/m)**	**pH**
	Young plants (up to 8 weeks old)	**Old plants (9 to 20 weeks old)**	**Young plants (up to 8 weeks old)**	**Old plants (9 to 20 weeks old)**		
Tomato	8	5	Every hour for 15 min	Every two hours for 15 min	2.12.-2	5.5-6.5
Pepper	8	5	Every hour for 15 min	Every two hours for 15 min	2.1-2.2	5.5-6.5
Cucumber	10	7	Every hour for 15 min	Every two hours for 15 min	2.1-2.2	5.5-6.5

Most of the farmers (75%) indicated having a nutrient solution monitoring system. Farmers having an EC and pH combo for manual monitoring of these variables formed 83%, while those having an auto-dosing system for automatic monitoring of EC and pH accounted 17%. (Figure 3.10) illustrates both systems used for monitoring EC and pH of hydroponic nutrient solutions.

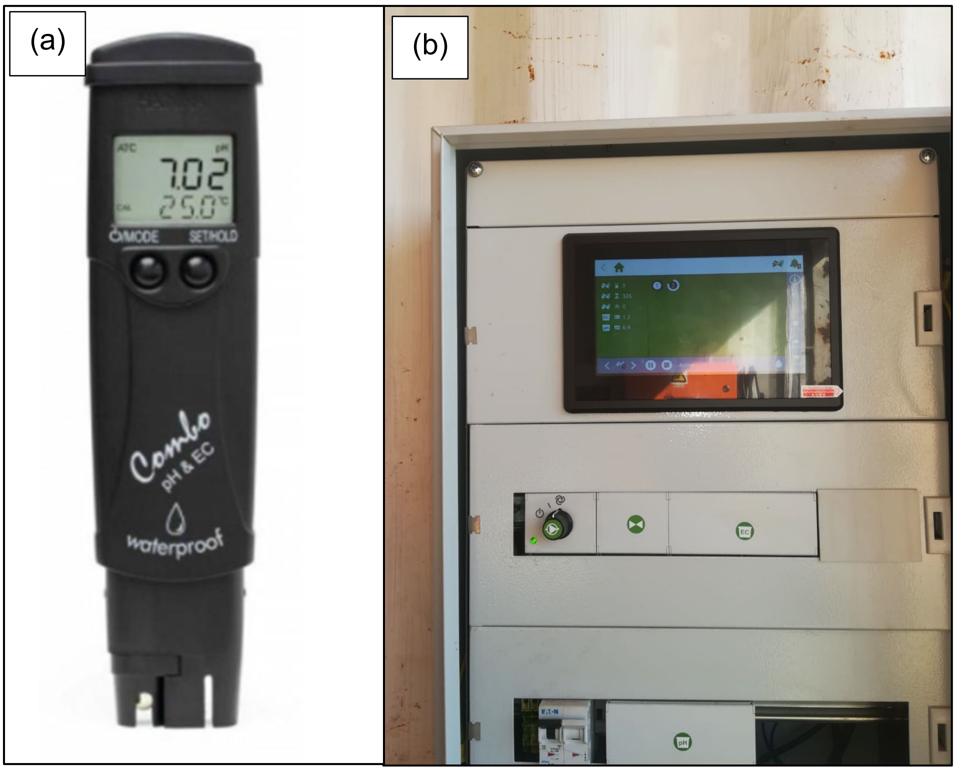

Figure 3.10: Electrical conductivity (EC) and pH monitoring using: (a) a combo for manual monitoring and (b) an auto-dosing system for automatic monitoring at farmers hydroponic sites (pictures taken by Ms Patricia Phasha – TC Women in Action Farming and Mr Tumelo Pule – AB Farms, 2021).

The auto-dosing system is also used to program irrigation scheduling, which is particularly crucial in an open-bag hydroponic system due to intermittent water flow cycles. Simpler irrigation monitoring systems can also be utilized for the same purpose, such as a Rain Bird irrigation control station, which was employed by the majority of farmers (88%). The water source for irrigation was highly variable among farmers. The most commonly utilized water source was borehole (63%), followed by municipal water (37%). The majority of farmers (75%) conducted chemical laboratory analysis of the irrigation water at least once per year. Most respondents indicated that the water quality was generally good for irrigation, while 13% of the farmers complained of high pH level (approximately 8) in borehole water. These farmers mentioned that they needed to apply significant amounts of nitric acid to lower pH to an acceptable level for crop production. All interviewed farmers were not registered water users and, as a result, they did not have water rights. Nonetheless, 63% of the farmers indicated not having problems of water shortages. The remaining 37% of farmers mentioned that they had a limited number of boreholes (a maximum of two), which often posed a constraint for adequate water availability. This is probably due to relatively low water delivery rates/capacity of the borehole. Some (25%)

of the farmers neither had knowledge of nutrient deficiency symptoms in crops nor solutions to overcome such problem. On the other hand, the remaining 75% of the farmers were able to identify the most common nutrient deficiencies by comparing symptoms of these deficiencies observed on crops to those illustrated in pictures found on the internet. They also had some knowledge of how to resolve the problem through application of nutrients into the system or flushing of planting bags in the event of salts build-up. A large number (75%) of the farmers conducted preventative spraying against major occurring pests and fungal diseases in the area and scouted for pests on a frequent basis.

3.3.5 Challenges faced by farmers in hydroponic crop production

Several challenges were identified by farmers in hydroponic crop production. These are illustrated in (Figure 3.11), in order of magnitude and importance based on farmers' responses. The major challenges encountered by the farmers in hydroponic crop production included lack of production infrastructure, limited access to markets, non-existence of GLOBALG.A.P. Certification, poor affordability of production inputs mainly seedlings, fertilizers and growing medium, limited water supply and lack of financial support or government incentives. The farmers proposed the following solutions to address the major challenges that were identified:

1) external funding support to expand existing hydroponics infrastructure (particularly for those farmers with a maximum of two tunnels, which comprises 38% of the total number of interviewed farmers), as well as to purchase production inputs;
2) acquisition of GLOBALG.A.P. certification in order to access private markets and
3) increased construction of boreholes or improve current borehole capacity/delivery rates.

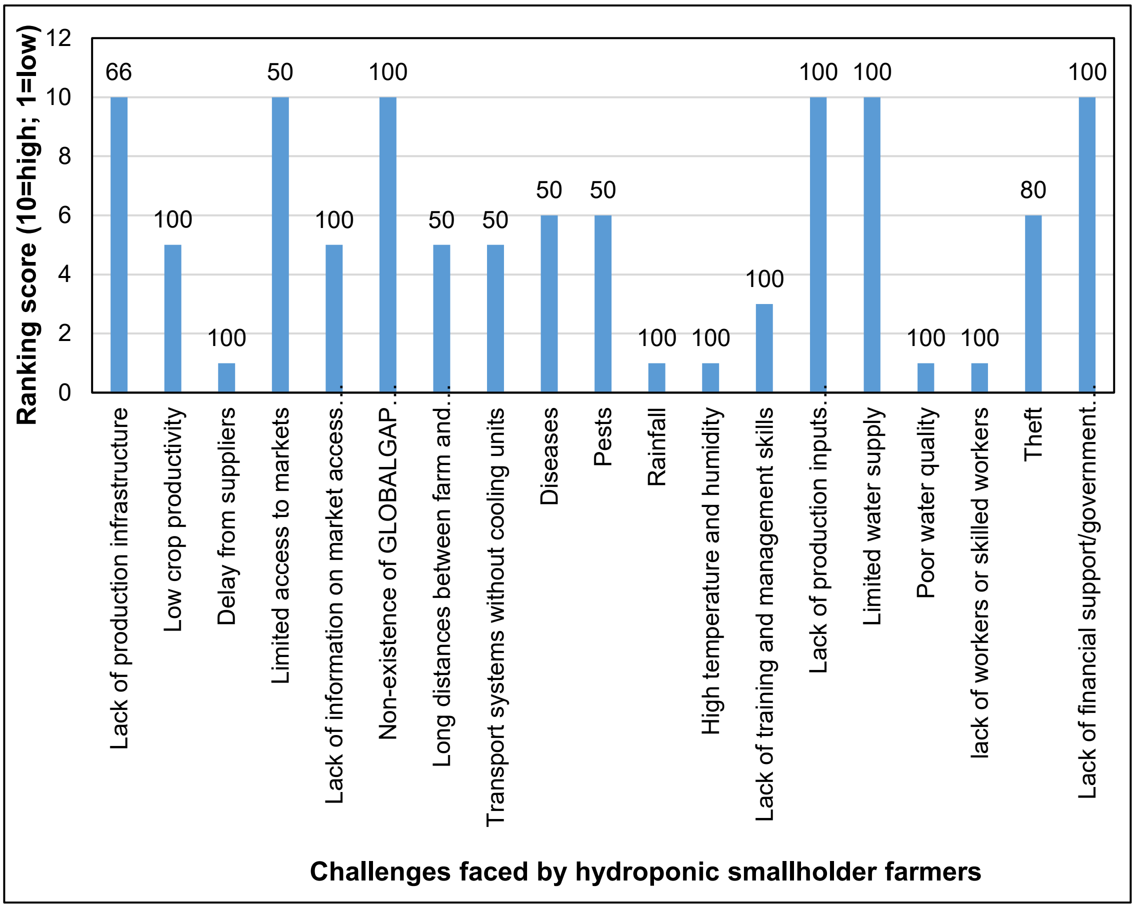

Figure 3.11: Percentage of respondent hydroponic farmers (indicated on top of each column) and respective responses in terms of their perception of the various challenges encountered in hydroponic crop production.

3.3.5.1 Human capacity and training needs in crop production systems

Farmers' responses for training needs was quite low (an average score of 3 out of 10 that indicates relative low priority). However, based on the interviews conducted with these farmers, it became clear to the research team that the majority of farmers still lacked knowledge and skills on several production aspects such as fertigation practices, seedling production and transplanting, vegetative propagation methods, pest and disease management, harvesting methods, infrastructure sanitation procedures, production and sales record keeping and market access strategies. Farm owners usually received training from external funding organizations such as GDARD, SAB and DALRRD for the duration of the projects implementation. Thereafter, they were primarily responsible for the transfer of such knowledge to their workers. Half of the interviewed farmers indicated that they had sufficient labour to conduct farming operations. A large number (75%) of the farmers employed part-time workers who were paid per amount of fresh produce harvested.

3.3.5.2 Hydroponic systems infrastructure availability and needs

According to the results presented in (Table 3.5), hydroponic commercial farmers had some infrastructure, particularly open-bag hydroponic systems operating in plastic tunnels. However, 60 to 80% of the interviewed farmers indicated the need for expansion of the existing systems in order to increase crop production and to meet market demands. It was interesting to note that only few farmers (13%) operate recirculating hydroponic systems, particularly the nutrient film technique (NFT). A very small number of the farmers (13%) are aware of the benefits of recirculating hydroponic systems, and therefore have the need to acquire them. Similarly, only a few farmers had tools for environmental monitoring (13% of farmers) and spraying (40% of farmers) (37% of farmers). Half of the interviewed farmers indicated a weighing scale for crop yield measurements and record keeping, while 75% of farmers had tools for nutrient solution monitoring. In contrast, only a minority of farmers (13% of farmers) could afford to have post-harvest equipment such as cold rooms and transport with cooling units, or even packaging material. Most farmers interviewed mentioned that they relied on middlemen who were better equipped to off-take their fresh produce directly from farm-gate to the markets. Thus, the middlemen were responsible for providing crates to package the bulk fresh produce and transportation to the markets. This also ensured that larger volumes/quantities of fresh produce were collected from various small-scale farmers to meet the market demand. Most farmers (87%) did not have water meters to monitor crop water consumption, which does not pose a major constraint since water supply quantification can be estimated from dripper delivery rate, duration and number of irrigation cycles. All interviewed farmers relied on electricity from Eskom to operate their hydroponic production systems, while only 50% of them had generators as a back-up in case of power failure.

Table 3.5: Farmers' hydroponic systems infrastructure and tools availability and needs.

Hydroponic infrastructure and tools	Percentage of farmers indicating availability of infrastructure/ tools within each category						Needs – % of farmers indicating the need
	Number of infrastructure/tools available						
	0	1 to 2	3 to 6	7 to 10	10 to 15	≥ 15	
Hydroponic infrastructure							
Tunnel	0	25	36	13	13	13	80
Shade net	50	50	0	0	0	0	60
Open-bag system	0	25	36	13	13	13	80
NFT system	87	13	0	0	0	0	13
Environmental monitoring							
Temperature and humidity data loggers	87	13	0	0	0	0	87
Manual rain-gauges	100	0	0	0	0	0	63
Nutrient solution monitoring tools							
EC and pH combo	25	62	13	0	0	0	63
Calibrated cups/containers	100	0	0	0	0	0	100
Spraying tools							
Knapsack	50	40	10	0	0	0	25
Mistblower	60	40	0	0	0	0	40
Protective clothing	10	0	0	90	0	0	40
Crop yield monitoring							
Weighing scale	50	50	0	0	0	0	100
Post-harvest equipment							
Cold room	87	13	0	0	0	0	87
Transport with cooling unit	87	13	0	0	0	0	87
Packaging materials							
Slicer	100	0	0	0	0	0	100
Blender	100	0	0	0	0	0	100
Wrapping machine	74	13	13	0	0	0	74
Irrigation system							
Water tank	0	37	63	0	0	0	63
Pump	0	100	0	0	0	0	100
Water meter	87	13	0	0	0	0	100
Additional							
Fence	50	50	0	0	0	0	50
Solar energy	100	0	0	0	0	0	50
Generator	50	25	25	0	0	0	25
Harvesting tools							
Pruning share	61	13	13	13	0	0	100
Ladder/steps	35	40	25	0	0	0	40
Crate	50	0	0	0	0	50	40

3.3.5.3 Hydroponic crop production costs

Farmers in the study sample were interviewed about costs incurred in crop production using hydroponics. Only a minority of farmers (40%) provided such information, while the remaining farmers did not respond because they did not keep proper records of input costs. It is important to note that the provided information does not reflect a standardized operation unit, but rather total production costs incurred by a certain farmer based on the scale of his/her production system. In general, looking at various input costs per farmer, the highest cost was on labor, followed by fertilizer, electricity, seeds/seedlings, fuel for transport services and purchase of pesticides. (Table 3.6) illustrates a typical example of input crop production costs incurred by a commercial small-scale farmer at West Rand, Gauteng Province, who produced fruity vegetable crops (tomato, cucumber and pepper) all-year-round using an open-bag system under protection. The farmer had two tunnels and one shade net. In this particular example, the water supply for crop production was sourced from a borehole and, as a result, the total variable cost excluded this input.

Table 3.6: A typical example of total variable input crop production costs incurred by a commercial hydroponic farmer at West Rand, Gauteng Province, who produced fruity vegetable crops (tomato, cucumber and pepper) all-year-round using an open-bag hydroponic system in two tunnels (10x30 m each) and one shade net (30x72 m).

Crop production input	**Total Cost (Rand per year per 2760 m^2 of area utilized for production)**
Electricity	8000
Fuel	5000
Seeds	6000
Fertilisers	10000
Pesticides	4000
Herbicides	200
Labour	15000
Total	**48200**

3.3.5.4 Marketing/ fresh produce distribution

Market selection for selling of fresh produce

The interviewed farmers supplied their fresh produce to different markets including formal national fresh produce markets (NFPMs) like Johannesburg and Tshwane markets (50% of these farmers used these markets as the main source of in-take), private markets such as “Made with Rural” through the use of middlemen like “Dew Crisp” (25% of the farmers used these markets as the main source of in-take) or directly to a warehouse or retailer (small quantities of fresh produce). The remaining 25% of the interviewees supplied their fresh produce to informal markets, which included farm gates and local markets. Farmers' fresh produce is supplied to NFPMs through market agents, who subsequently sell the produce to wholesalers, wholesaler-retailers and retailers. Farmers get better prices for selling their produce to NFPMs when compared to informal markets. However, the selling of fresh produce to NFPMs incurs market agent and market management costs, and if the produce is not bulk packaged prior to its delivery, farmers get higher chargers for offloading it to the market. Those who sell their fresh produce to private markets get even better prices compared to NFPMs, but since it requires a middleman to connect them to these markets, their generated income is often much lower than what could be expected. The middleman ensures that small-scale farmers meet all requirements for a good quality fresh produce supply to the market (only grade A produce is acceptable), which is a criterion for compliance with GLOBALG.A.P. certification possessed by the middleman. Thus, farmers need to assess and evaluate their available options in terms of cost and benefit to make better decisions on where to sell their fresh produce. (Figure 3.12) illustrated a diagram of hydroponic commercial farmers' fresh produce supply chain.

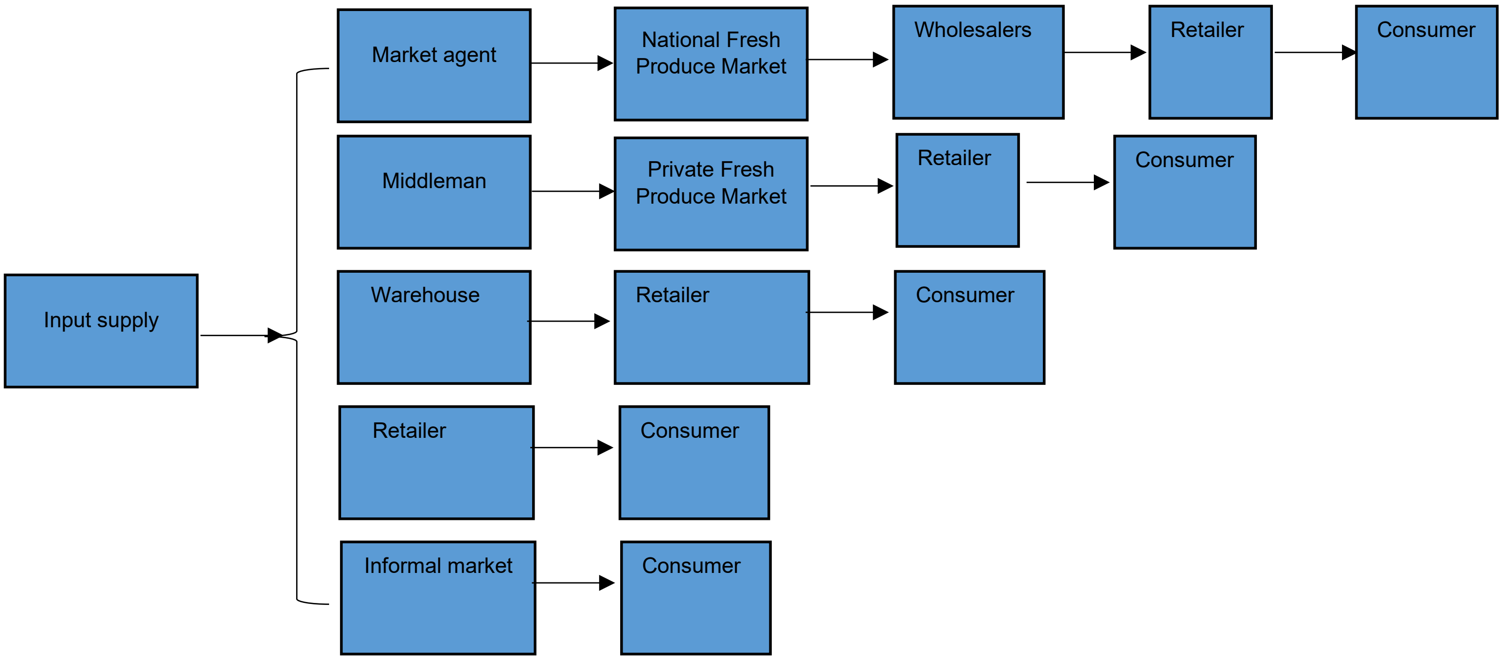

Figure 3.12: Hydroponic commercial farmers' fresh produce supply chain in the Gauteng Province of South Africa.

Market access

The majority of surveyed farmers (75%) indicated that they did not have formal contracts with markets, but they had regular clients to whom they supplied their fresh produce. These included retail supermarkets such as Spar and Pick' n Pay. The remaining 25% of the farmers had contracts particularly those using services of middlemen, which were renewable on an annual basis. Fifty percent of the interviewees indicated not being able to meet market demands due to low crop production as a result of limited infrastructure capacity. However, even those farmers with larger infrastructure capacity (39% of the total number of interviewed farmers having at least seven tunnels) could not produce sufficient quantities to meet the market demand, suggesting that systems management at production level could also contribute to the low crop productivity and restricted market supply. Those farmers who supplied their fresh produce directly to middleman (13%) were only responsible for producing and harvesting of produce, while middleman duties were to package the produce in crates and subsequent packaging and transportation to private markets. 25% of the surveyed farmers hired transport to move the fresh produce to the markets, while 62% of them used their own transport. The fresh produce supplied to the middleman was combined with those sourced from various farmers (bulking up) in order to have sufficient quantities to meet market demands, while those supplying to NFPMs were not obliged to do so. The selling price of fresh produce was often determined by the buyers, particularly when the produce was supplied to middlemen or market agents. Only 25% of farmers packaged their fresh produce prior to delivering to the markets. Only a minority of the farmers (13%) had a GLOBALG.A.P. certification, which was acquired through the assistance of external funders such as SAB Urban Agriculture. These farmers were able to supply their fresh produce directly to retailers. Other farmers indicated that they did not have such certification because the process was too complicated and costly.

Market access challenges and proposed solutions

Table 3.7 presents a list of challenges faced by hydroponic farmers in terms of market access. It also indicates the proposed solutions to address such challenges, based on farmers' suggestions and in some instances observations by the research team. The major challenges encountered by the hydroponic commercial farmers in the Gauteng Province included low quantities of fresh produce mainly due to lack appropriate production management skills and in some instances limited hydroponic infrastructure capacity, lack of transport with a cooling system, high transport cost relative to the amount of fresh produce to be transported, lack of market advertisement, GLOBALG.A.P. certification to enter private markets and value-adding technologies such as packaging and branding. Farmers should invest on appropriate post-harvest handling practices, like sorting and grading after harvesting, precooling, cleaning and disinfection, packaging, storage and refrigerated transportation in order to maintain good marketable quality and extended shelf life of fresh produce (Arah et al., 2016). This is particularly crucial for fresh produce farmers whose source of supply is mainly NFPMs, because the market price of fresh produce is highly variable on a daily basis depending on the actual quality of the produce amongst other factors. The implementation of most of these practices requires that farmers be equipped with the necessary technologies, which is often impossible due to existence of limited finances and lack of external funding support. As a result of long transportation distances and lack of refrigerated vehicles, there is a considerable perishability of small-scale farmers' fresh produce, which consequently affects its market price negatively. The relatively cool weather is also a problem in Gauteng, particularly during the winter months when production of fruity crops can only be possible using temperature-controlled structures.

Table 3.7: Hydroponic farmer's perceptions of the various challenges encountered in terms of market access and their proposed solutions to address such challenges.

Market challenge	level of magnitude (10 = major; 1 = minor)	Proposed solution
Small quantities of fresh produce	10	1. Combine fresh produce with other farmers; 2. Expand the number of existing hydroponic infrastructure; 3. Utilize more of the available space for crop production
Lack of transport	10	Purchase or hire a refrigerated truck
High transport cost	10	1. Acquire own transport; Transport combined fresh produce with other farmers
Poor road conditions	1	
Long distances between the farm and market	10	1. Supply closer markets; 2. Use refrigerated trucks
Lack of bargaining power	1	
Lack of market information	5	
Lack of marketing advertisement	10	Advertise more farmers' fresh produce
Lack of GLOBALG.A.P. certification	10	Undergo certification process
Lack of post-harvest and value-adding technologies	10	1. Set-up of a processing facility; 2. Increase external funding sponsorship; 3. Gain access to private markets
Poor quality of the produce	1	
Inappropriate crop choice	1	

Market challenge	level of magnitude (10 = major; 1 = minor)	Proposed solution
Weather conditions	10	Increased utilization of temperature-controlled hydroponic systems to allow continuous crop production and market supply all-year-round
Business insurance	10	Increase income generation to afford insurance

Cost-benefit evaluation

Farmers were questioned whether they were willing to share the information on income and profit they generated from the selling of their fresh produce and only 25% of farmers agreed to share such information. Table 9 below summarizes total variable cost incurred by farmers per crop, income and profit gained for four crops (jalapeno and cabbage planted under a shade net structure and green pepper and brinjals cultivated in an open-bag hydroponic system under a non-temperature-controlled plastic tunnel). (Table 3.8) also presents extrapolated results for one hectare to evaluate potential total variable cost, income and profit generated if farmers' available infrastructure can be expanded. However, before considering that, it is suggested that appropriate knowledge and skills of production, systems operation and market access strategies can be transferred to farmers to ensure increased yield, quality and farming profitability. Although the total variable costs involved in hydroponic production per unit area are much higher (R15-R17 per m^2) compared to protected soil cultivation (R5-R6 per m^2), the former allows for optimum cultivation of high-value crops/cultivars with an indeterminate growth like peppers and brinjals, which are generally sold at higher prices in the market. The yield of these crops is usually considerably higher compared to their determinate growth habit counterparts that are often cultivated under open-field. This is because hydroponic production is usually implemented under protected environmental conditions, which limits pest and disease infestation, damage by hail, heavy rainfall, strong winds or excessive heat. In addition, the micro-climatic conditions inside the plastic hydroponic structure are conducive for rapid growth and development of the crop due to a much faster accumulation of thermal time requirements compared to the outside environment. All these factors combined with unlimited nutrients and water supply to plant root zone results in considerably higher crop marketable yield and quality with hydroponics compared to soil cultivation, leading to higher income generation and profitability with the former compared to the latter cultivation system, particularly when crop production is implemented at a larger scale (Souza et al., 2019). Also, at a large production scale, hydroponic farmers can be in a better position to meet the market demands by producing sufficient fresh produce, which would address the major challenges encountered by these farmers to access private formal markets. In order to achieve this, farmers need to improve their knowledge and skills of crop production as well as hydroponic systems operation and management. This will ensure that farmers meet the standard requirements of good marketable fresh produce in order to become more competitive in the market. In addition, farmers can invest in simple value-adding technologies such as packaging and branding. Proper records of production inputs, input costs, income and profit generated should be kept and evaluations should be carried out on a frequently basis to assess the sustainability of the business. The above-mentioned suggestions will assist farmers in acquiring GLOBALG.A.P. certification more easily, which will enable them access better markets. This will contribute to a more sustainable and profitable farming, with great potential for expansion of their infrastructure production capacity.

Table 3.8: Total variable cost, income and profit made by farmers for four crops (jalapeno and cabbage planted in soil under a shade net structure and green pepper and brinjals cultivated in an open-bag hydroponic system under a non-temperature-controlled plastic tunnel), per structure and per hectare of crop production.

Crop	Production system	Structure size (m^2)	Growing season	Quantity of fresh produce	Cost (Rand)		Income (Rand)		Profit (Rand)	
					Per structure	Per hectare	Per structure	Per hectare	Per structure	Per hectare
Jalapeno	Soil under shade net	2160	Summer	3000 kg	12960	60000	48000	222222	35040	162222
Cabbage	Soil under shade net	2160	Winter	6000 heads	10800	50000	42000	194444	31200	144444
Green pepper	Open bag under non-temperature-controlled plastic tunnel	300	Summer	2400 kg	5239	174633	19200	633600	13961	458967
Brinjals	Open bag under non-temperature-controlled plastic tunnel	300	Summer	3000 kg	4500	150000	21000	693000	16500	543000

3.4 Market characteristics analysis

3.4.1 Market sales of fresh produce

Several agents of the Tshwane Fresh Produce Market, to which the majority of smallholder farmers supply their fresh produce, were interviewed to understand how the national formal markets operate in terms of sales of fresh produce. (Table 3.9) lists high-value crops with increased market demand, their average market price, estimated fresh produce losses and potential income generation. Most of the crops presented in (Table 3.9) are generally produced in summer when the environmental conditions are adequate for their growth and development, but farmers also try to grow these crops during the winter periods in order to have all-year-round market supply and continuous income generation. Since winter productions are off-season for the majority of the crops listed in (Table 3.9), the quantity supplied to the market is usually low, which results in increased market prices during this period. Winter productions generally incur low fresh produce losses at pre- and post-harvest stages due to relatively cool weather conditions. Hydroponic crop production in plastic tunnels can be a solution to address the problem of limited market supply during winter periods, particularly when temperature-controlled structures are adopted. However, only a minority of commercial farmers have such systems, which they have acquired through external funding initiatives by the national government and NGOs.

As illustrated in (Table 3.9), crops with great potential for high-income generation are mostly fruity crops (tomatoes, peppers and cucumbers). These are generally more suitable for production in an open-bag non-recirculating hydroponic system, although the cultivation of tomatoes has been successfully tested at ARC in a gravel-film recirculating hydroponic system (Maboko et al., 2011; Maboko and Du Plooy, 2013; Maboko et al., 2017). High-value crops with increased potential for good income generation, which are well suited for production in recirculating hydroponic systems, include lettuce, baby okra and baby marrow. Several studies have shown successful production of lettuce in both gravel-film (Chiloane, 2012; Maboko and Du Plooy, 2013; Mampholo et al., 2017) and nutrient film techniques (Sace and Estigoy, 2015; Touliatos et al., 2016; Goddek and Vermeulen, 2018). Research studies on okra and baby marrow cultivated under recirculating hydroponic systems are still infrequent, which opens opportunities for further investigation under the current WRC project. Surprisingly, sweet basil fresh produce market supply was quite low, but its sales market price is considerably high (R100 per kg), suggesting good potential to be cultivated for high income generation. However, sweet basil fresh produce market loss is enormous (60% of the total amount supplied to the market), which suggests that the implementation of post-harvest handling practices and agro-processing/product development technologies should be considered for this crop.

Table 3.9: Average fresh produce supply, market sales and total income generated per day per commodity in the Tshwane Fresh Produce Market. Only high-value crops with potential for adequate production in hydroponics have been selected and displayed for evaluation.

Group	Crop	Growing season	Quantity supplied per day(kg)	Daily average market price (R)	Quantity sold per day (kg)	Quantity sold per day (%)	Fresh produce loss (%)	Market agent commission (%)	Market management (%)	Total income per day (R)
Leafy vegetables	Spinach	Summer	18500	2	17000	92	8	9	5	29240
	Lettuce	Winter	8000	24	7500	94	<1	9	5	154800
	Cabbage	Winter	140000	2	128000	91	5	9	5	220160
Sub-total										**404200**
Fruity vegetables	Brinjal	Summer	3400	6	2300	68	5	9	5	11868
	Sweet pepper	Summer	62000	6	55000	89	2	9	5	283800
	Tomato	Summer	350000	9	295000	84	5	9	5	2283300
	English cucumber	Summer	51000	11	48000	94	1	9	5	454080
Sub-total										**3033048**
Herbs	Leeks	Winter	115	11	53	46	50	9	5	501
	Spring onion	Winter	365	16	243	67	5	9	5	3344
	Sweet basil	Summer	35	100	3	9	60	9	5	258
Sub-total										**4103**
Microgreens	Baby marrow	Summer	2000	35	2000	100	0	9	5	60200
	Baby sweet corn	Summer	650	26	150	23	55	9	5	3354
	Baby okra	Summer	12500	11	7300	58	30	9	5	69058
	Patty pan	Summer	270	45	263	97	1	9	5	10178
Sub-total										**142790**
Total										**3584141**

3.4.2 Additional market characteristics

Based on the interviewed market agent responses, 90% of the fresh produce suppliers in NFPMs are commercial small-scale farmers, which include emerging commercial farmers. Market suppliers comprise all races, ages and genders, but African black male farmers (95-98%), aged 36-45 years old, form the biggest group of small-scale suppliers. Nonetheless, large-scale commercial farmers still dominate the majority of the supply to the NFPMs with between 80 and 90%of the fresh produce, while small-scale producers supply the remaining variable volumes. The fresh produce supplied to the Tshwane Market comes primarily from Limpopo, Gauteng and Northwest provinces. Farmers supplying fresh produce to national formal markets do not require GLOBALG.A.P. certification, but they must comply with standard requirements that are needed for human consumption (in other words, the produce should be as fresh as possible, with a good colour/appearance). The surveyed market agents also indicated that there is a market demand for packaged herbs (15% of the total number of clients) and leafy vegetables (20% of the total number of clients). Also, if farmers could bulk-package their fresh produce prior to its delivery to the market, they could stand a chance of selling the produce at better prices due to quality preservation/maintenance and easy offloading at the market site, which would reduce the market commission chargers related to labour cost.

3.5 Complementary research using secondary data

3.5.1 Weather conditions across Gauteng province and associated impact on fresh produce quality

3.5.1.1 Weather variability and its impact on agricultural production

Climate change directly affects agricultural production, since the sector is very sensitive to climatic conditions. The agricultural sector is one of the most vulnerable sectors to the risks and impact of global climate change. Agricultural production remains the main source of livelihood for most rural communities in Africa, providing employment to more than 60% of the population and contributing about 30% of gross domestic product (Musvoto et al., 2015). Agriculture is particularly relevant to the green economy in developing countries, as it holds the potential to address some of the problems of poverty and rapid urbanisation, which occur in many countries, including South Africa (Musvoto et al., 2015). Southern Africa is expected to experience increases in temperature and declining rainfall patterns as well as increased frequency of extreme climate events (like droughts and floods) due to climate change (IPCC, 2011). The World Bank (2010) stated that South Africa has been getting hotter over the past four decades with average minimum monthly temperature at 13°C and average maximum monthly temperature at 26°C. There was also an increase in the number of warmer days as well as a decrease in the number of cooler days. Moreover, the country average rainfall, estimated at 450 mm per year, is well below the global average of 860 mm (World Bank, 2010). In addition, surface and underground water resources are very limited. Agriculture is expected to be the worst affected by these changes because it is highly dependent on climate variables such as temperature, humidity and precipitation (IPCC, 2011). According to Kgakatsi (2006), climate change can be regarded as the silent enemy likely to affect already high risk and stressed agro ecosystems as the effects of climate change are not immediately visible. Gauteng Province is also vulnerable to climate variability as agricultural production depends on climatic conditions and mostly on the quality of the rainy season. It is therefore, important to develop and implement effective adaptation measures to mitigate climate-related risks on crop production, including for Gauteng Province. A long-term climatic data analysis for the past 15 to 19 consecutive years (2000/2004 to 2019) of the three regions (eastern, western and Tshwane regions) in the Gauteng Province revealed slight differences in weather conditions across them. The eastern region was found to be generally cooler, more humid, with lower atmospheric evaporative demand (mean annual temperature of 16.5°C, relative humidity of 58.9% and reference evapotranspiration of 1215.3 mm), when compared to the Tshwane region (mean annual temperature of 18.4°C, relative humidity of 57.4% and reference evapotranspiration of 1377.2 mm), and the western region (mean annual temperature of 17.9°C, relative humidity of 54.1% and reference evapotranspiration of 1315.9 mm) (Kruger, 2004). The monthly average values for maximum and minimum temperature and relative humidity, as well as monthly totals of grass reference evapotranspiration (ETo) during the crop growing season, for the past 15 to 19 consecutive years for each experimental site are presented in (Table 3.10).

Table 3.10: Monthly average solar radiation (Rs), maximum (Tmax) and minimum (Tmin) air temperatures, maximum (RHmax) and minimum (RHmin) relative humidity, as well as monthly total reference evapotranspiration (ETo) over a long-term period of 15 to 19 consecutive years (2000/2004 to 2019) for each experimental site (Chiloane, 2019).

Month	Atmospheric variability					
	R_s (MJ m^{-2} d^{-1})	T_{max} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	ET_o (mm $month^{-1}$)
	Eastern region					
October	20.02	26.10	11.13	83.77	28.01	128.95
November	21.16	26.10	12.53	87.87	33.24	126.23
December	21.02	26.52	14.25	92.37	39.40	131.71
January	20.61	26.73	14.60	93.29	41.71	119.94
February	18.95	26.52	14.12	94.66	41.22	103.74
March	16.71	25.46	12.46	94.23	39.35	104.11
	Tshwane region					
October	23.32	28.88	13.16	79.76	27.02	150.55
November	24.26	28.23	14.53	85.28	34.35	148.10
December	24.03	28.24	15.85	88.72	40.35	150.53
January	23.81	28.83	16.15	90.38	41.24	143.66
February	22.40	29.60	15.83	90.19	37.05	125.82
March	19.77	28.25	14.19	90.00	37.43	118.41
	Western region					
October	21.53	29.47	11.01	74.69	19.83	141.89
November	22.54	29.57	12.86	79.53	25.01	143.97
December	21.15	29.84	15.10	84.79	32.87	140.90
January	22.04	30.52	15.51	85.19	31.85	145.29
February	19.15	30.22	14.62	90.04	33.61	114.27
March	17.12	28.44	12.77	89.94	34.68	109.82

3.5.1.2 Temperature as the main influencer of fresh produce quality

Temperature is one of the main environmental factors that influence the quality of farm produce (Table 3.11). Extremely low temperature causes chilling or freezing injury, while high temperature causes increased respiration and ethylene production as well as water loss, which results in a decrease in internal quality, shrivelling and premature softening. Other factors causing product quality deterioration includes initial quality, environmental humidity, water loss, atmospheric gas concentration, mixed loads, physical injury and stress and transport conditions such as surface road conditions and time of the day (Vigneault et al., 2009).

Without cold storage, most fruits and vegetables will not stay fresh for more than a few days and as soon as fresh produce is harvested, it begins to deteriorate with potential for bacteria and fungi attack. The low temperatures inside cold storage units halt the growth of these pathogenic microorganisms, ensuring that spoilage of fruits and vegetables is kept to a minimum. Refrigeration and blast freezing are equally popular options for many vegetables and some selected fruits. This is why the cold storage units have a varied temperature range for both freezing and chilling options.

Another important benefit of cold storage units is that they are highly customisable, something that is particularly important when storing fresh fruits and vegetables. Temperature and humidity levels can vary greatly between produce, making customisation essential. Cold storage for fruit and vegetables also comes in a variety of sizes, including mini chillers that are perfect for caterers and mega cold stores made with large distributors in mind. There is rarely a one temperature fits all solution to storing fruit and vegetables. This is because factors such as crop maturity, the season of harvest and crop origins all play a part in calculating the optimum temperature requirements. A general ‘rule of thumb’ is that cool season fruit and vegetables, such as kale and sprouts, should be stored at around 0-2°C. Warmer season fruit and vegetables, like cucumber and tomato, are best stored around 7-15°C. However, there are exceptions to the rule (Table 3.11), as some fruit and vegetables are more greatly affected by low temperatures than other (https://www.crscoldstorage.co.uk/news/cold-storage-fruit-and-veg.html).

Table 3.11: Recommended refrigeration guideline for fresh fruit and vegetables (https://www.crscoldstorage.co.uk/news/cold-storage-fruit-and-veg.html).

Product	Temperature (°C)	Ventilation setting (cm^3/hr)	Relative humidity (%)	Approximate storage days
Apples	-1 to +4	10 to 60	90 to 95	2 to 7 months
Bananas, green	+13 to +14	25 to 60	85 to 95	18-22
Beans	+4 to +7	20 to 30	95 to 98	7-10
Cabbage (early)	0	20 to 60	90 to 98	21-42
Carrots	0	10 to 20	90 to 95	28-180
Cauliflower	0	20 to 60	90 to 98	14-21
Eggplants	+8 to +12	10 to 15	90 to 95	7-14
Figs (fresh)	-0.5 to 0	0 to 5	85 to 90	7-10
Garlic	0	0 to 15	60 to 70	6 to 7 months
Ginger	+13	10 to 15	65 to 75	4 to 6 months
Grapes	-1 to 0	10 to 15	90 to 95	1 to 5 months
Lemons	+11 to +15	15 to 25	85 to 95	1 to 3 months
Lychees	+2 to +6	10 to 15	90 to 95	21-35
Mandarines	+4 to +8	15 to 25	90 to 95	21-56
Mangoes	+10 to +14	25 to 30	85 to 95	14-21
Onion (dry)	0 to +2	10 to 15	65 to 75	6 to 9 months
Oranges	+2 to +10	15 to 25	85 to 90	1 to 3 months
Papayas	+10	25 to 30	85 to 95	7-21
Pears	0	15 to 25	90 to 95	1 to 6 months
Pineapples	+8 to +12	15 to 25	85 to 90	7-21
Plums	0	15 to 25	90 to 95	15-20
Potatoes (table)	+4 to +8	15 to 25	85 to 95	2 to 12 months
Strawberries	-0.5 to 0	10 to 15	90 to 95	3-8
Tomatoes	+7 to +15	15 to 30	65 to 90	7-28

3.5.2 Production risk management mechanisms for commercial small-scale farmers

Agriculture is characterised by a high variability of returns, such that farmers cannot predict with certainty the amount of output they will produce. Thus, agricultural risk is associated with unpredictable circumstances which determine the final output, value and cost of any agricultural production process (Cervantes-Godoy et al., 2013). These risks are influenced by several factors, ranging from weather variability, natural disasters, knowledge gaps and lack of support on the management of hydroponic systems, uncertainties in yields and prices, imperfect markets of financial services, institutional settings, personal risks, etc. In the case of developing countries, and more specifically that of smallholders, farmers are likely to be particularly vulnerable to certain risks and the consequences of these can be extreme, in some cases even pushing resource-limited smallholder farmers into deeper poverty (Cervantes Godoy et al., 2013).

3.5.2.1 Input supply

According to a survey study conducted with smallholder fresh produce farmers in the Gauteng Province of South Africa, farmers encounter two major risks are during the input supply stage, namely the costs and quality of the inputs (Louw and Jordaan, 2018). This is particularly true for hydroponic farmers, because when suppliers realize that the farmers have very limited knowledge on the subject, they take advantage by supplying or providing the farmers with inputs and services of poor quality. Most of the farmers in the sample (62%) complained about the costs of the inputs such as growing medium and hydroponic fertilizers, citing that they were too expensive. Hence, farmers were forced to cut back on their input purchases and reduce their levels of production. The yield and income realised also declined. In addition, the low production levels may exclude farmers from selling to formal markets that require consistent deliveries to the market. Several interviewed farmers (15%) in the study conducted by Louw and Jordaan (2018) reported that some of the inputs they purchased were of poor quality, that seed germinated poorly and often produced vegetables of poor quality, which failed to sell in formal high-value markets.

Also, lack of access to credit is noticeable for daily expenditures in an agribusiness. Working capital is often lacking in small-scale businesses. Especially in the period between planting and harvesting, small-scale agribusinesses have little working capital available, because a great part of their savings is spent on farm inputs. Funds, which can be used to, for instance, clear the lands or repair security equipment, is often non-existent. Lacking capital makes the farm also more prone to risks (Collier and Dercon, 2013). Additional disadvantages for small-scale farmers are the inability to invest in capital intensive equipment such storage equipment, traceability systems, process monitoring systems and (repeated) capital investments to satisfy the (evolving) quality and safety requirements of buyers (Poulton et al., 2010). Also, small-scale farmers often lack business skills and training to increase their farming efficiencies, profitability and sustainability (Louw and Jordaan, 2018). On the contrary, large-scale agricultural businesses can generally produce at a higher efficiency rate because mostly because they have the advantage of being more capital intensive and have increased possibilities to mobilize funds. Small-scale farmers often do not have access to credit, because sufficient collateral is lacking to acquire loans. Therefore, moneylenders rather provide capital to large firms than small firms. Farms often spend this capital on lumpy investments (e.g. machinery, oxen) which enhance production efficiency (Collier and Dercon, 2013). Additionally, capital is necessary to impose technological changes (Collier, 2008b), which implies that large-scale farms are more technologically evolved than small-scale farms. Examples of recent technological changes in agriculture are crop or cultivar breeding and vertical systems. These technological changes initiated efficiency gains for labour supervision (Deininger and Byerlee, 2012) in contrast to small-scale farms who rely on family labour. Large farms also have the ability to employ highly trained managers, who can gain them efficiency advantages under conditions of rapidly changing markets and technologies (Deininger and Byerlee, 2012).

3.5.2.2 Production

Crop performance depends on biological processes that are influenced by weather, and by pests and diseases, amongst others, while incorrect or poor irrigation scheduling may lead to low yields. Hail could damage the hydroponic infrastructure (plastic covered tunnels) used for crop protection. When farmers plant crops and invest in infrastructure, they do not know for sure whether there will be a hailstorm. They do not even know if there will be a problem with pests or diseases. Outbreaks of pests and/or diseases can cause major yield losses in crops and livestock. The input costs that farmers incur to plough their land, plant, cultivate, weed and fertilize their crops or to care for their livestock can also increase as the result of such unpredictable circumstances Farmers produce without complete knowledge about what will happen to their operation. Another source of production risk is equipment. A farmer's tractor may break down during the production season affecting the farmer's ability to harvest in time, therefore affecting yields. If the farmer is using a new technology without prior tests regarding its performance, the farmer will not know whether it will perform as expected or whether it will reduce costs and/ or increase yields. Similar production risks also apply to hydroponics production. For example, the production of seedlings in a nursery using seedling trays, is one of the primary steps for crop production, and if seeds do not germinate in the seedling trays, what will be the impact on production and farm family income and survival condition?

This will increase the farmer's input costs and also delay the production cycle/season since more seeds will have to be planted. During the production stage, farmers reported unpleasant weather conditions (e.g. frost and hail damage to infrastructure), pests and diseases, water shortages and unskilled labour as the major risks affecting their fresh produce business (Louw and Jordaan, 2018). Weather-related risks, pests and diseases were reported to affect both the quantity and quality of the produce, thus creating challenges for farmers to sell to the high-value markets. A shortage of water was reported by farmers who use municipality water for irrigation. They stated that because of the high cost of water, they had reduced the amount of land cultivated to reduce water consumption. This reduction in land cultivated resulted in farmers producing a limited quantity of produce. Farmers who reported unskilled labour as a challenge indicated that some of their workers lacked the knowledge on how to apply chemicals properly, and in some cases, workers were reported not to mix fertilizers properly, which affected the quantities harvested and the quality of the produce.

The issue of production risk has also been raised by the World Bank, which for a few years has been drawing up strategies that can be implemented by specific countries (Mahul and Stutley, 2010). The strategies particularly emphasize preliminary risk assessment and the importance of identifying its sources as well as taking appropriate remedies. They may include any preventive measures designed to prevent risk, namely improving water management, selecting appropriate production means in the form of hydroponics to avoid soil borne pathogens/pests or implementing early warning systems against natural disasters which may have a negative effect on production.

3.5.2.3 Marketing

The retailing of food in South African cities takes place through five primary channels, including fresh produce markets, supermarkets, informal traders, restaurants and fast food chains. In addition, there are incipient alternative food retail networks, such as farmers' markets and buyers' clubs, which cater for very specific consumer groups. Municipal government plays an integral role in shaping the food retail environment and therefore food security (Battersby et al., 2015).

A study on the marketing of fresh produce in the developing countries was conducted by Rich et al. (2009), which employed the supply chain analysis approach and made use of both primary and secondary data to conduct the supply chain risk assessment. Post-harvest and marketing risks that were identified in their study included low market prices, lack of access to markets, lack of transport, market competition, poor produce quality and a lack of packaging material. In general, these challenges relate quite well to those that were identified in the present study conducted on commercial hydroponic farmers in the Gauteng Province of South Africa.

Small-scale agribusinesses are faced with higher transaction costs such as unskilled labour supervision, knowledge/skills, motivation, etc. than large-scale agribusinesses. The high transaction costs are a large source of farmers' poverty and missing links to the market. Beside their scale disadvantages, these transaction costs are exacerbated by small-scale farmer's poverty, health uncertainty, lack of access to capital and low levels of education. In addition, poor communication channels and lower economic activity in the poor areas where they reside further increase the transaction costs (Poulton et al., 2010). Especially regarding marketing, large businesses have better opportunities to gain higher profits. Firstly, the market share of small-scale farmers has weakened because of an increased establishment of supermarkets during past decade in South Africa. These supermarkets established value chains which weakened the business relationships with small-scale farmers. Supermarkets look for relationships with producers who can produce significant and regular quantities of a certain range of products. Additionally, supermarkets require producers to respond rapidly to consumer changes (Reardon et al., 2005). Unfortunately, small-scale farmers cannot meet their market demands in terms of quality and quantity that is required and, as a result they struggle to enter existing value chains. Secondly, small-scale farmers can be victims of opportunistic behaviour of traders. Farmers are often cheated out of a profit; for example, due to poor quality inputs, “fixing” of scales or measures by suppliers or traders (Poulton et al., 2010). The weak market position of small-scale farmers can be exploited since large companies can have more bargaining power. This can reduce their input price and increase their output prices. In Argentina, a study on this topic recorded a reduction in input prices and increase in output prices of between 10 and 20% (Poulton et al., 2010). Thirdly, large-scale businesses have increased opportunities to gain profits on markets, as these businesses can react faster to evolving market demand. Large-scale businesses can be more efficiently organized and have increased access to working capital (Collier, 2008), which can result in increased profit margins.

Kahan (2008) reported that the price of farm products is influenced by the supply and demand for the product as well as the cost of production. Supply of agricultural product is affected by a number of production decisions made by farmers and by the weather and other factors that influence yields. On the other hand, demand for agricultural products is affected by consumer preference, consumers’ level of income, the strength of the general economy, and the supply and price of competing products. Although input costs tend to be less variable than output prices, when combined with yield variations, the cost of production becomes the main source of risk. When farmers plant crops they do not know certainly what prices they will obtain for their products.

3.5.2.4 Risk management for commercial fresh produce farmers

Risk management refers to actions taken by farmers to increase rate of success of the farming business. Farmers achieve this by influencing future events and by limiting the negative effect of those events, while many farmers try to do both. A good risk management strategy will try to act on both events and their consequences (Kahan, 2008).

Risk perception can affect economic behaviour, and thus the decision to adopt a specific risk management strategy (Alamerie et al., 2014). Some of the risk management strategies which farmers can adopt include the following: risk-reducing inputs are production inputs that improve the chances of better quantity or quality of farm products. Fertilizers are used to reduce the risk of low yields. Pesticides and Integrated Pest Management (IPM) practices are used to reduce the risk of crop damage. Irrigation is used to reduce the risk of crop moisture stress in hydroponics. Not all inputs necessarily reduce risk. For example, even if fertilizer is used, the crop still depends on irrigation, which may or may not be favourable. When moisture levels in the growing medium are low, using fertilizer can still result in low yields (Palinkas and Szekely, 2017). Farmers, however, do not experience only one kind of production risk at a time. They often experience the risk of unfavourable weather, pests and diseases at the same time. Using a single risk-reducing input, like high yielding variety will not prevent low yields caused by pest and insect damage. To determine whether an input will reduce the risk of low yields, farmers must look at a number of factors at the same time. They should think about the effect the input is most likely to have on their crop, given other factors that also affect production. Farmers must ask themselves whether the income expected by using the input is high enough to compensate for the increased risk involved. Essentially, farmers must weigh up the costs and benefits of using an input as a risk reducing strategy (Fielke and Bardsley (2014, Kahan, 2008).

Risk-reducing technologies can reduce risk by learning about and applying new technologies and practices designed to address specific risks common to their area of production. For example, new varieties of seed are being developed which are bred with certain characteristics, including the following: disease- and pest-resistant; high water use efficiency and appealing quality attributes such as high firmness, adequate fruit size and shape as well as great colour to improve marketability (Chang and Tsai, 2015).

Farming system flexibility is another critical strategy for risk management. A flexible farming system ensures the farmer to make urgent or short-term changes in production and sales. Farmers who sell cash crops may also reduce risk by using available funds to allow them to change to another commodity once the price of the main cash crop falls. By keeping their farm systems flexible, farmers are able to make decisions in response to changing circumstances. While working with general production plans, they should keep their options as open as possible in order to respond to opportunities and risks as they occur (Kahan, 2008, Gebreegziabher and Tadesse, 2014).

3.6 Supply chain and distribution channels for commercial fresh produce farmers in Gauteng

Supply chain and distribution of agricultural fresh produce is a systematic channel created to ensure produce reaches consumers (Hewett, 2012). South Africa has been reputable producer and distributor of agricultural produce (Melembe et al., 2020). Due to South Africa's geographical landscapes and climate multiple different regions participate in agricultural production. Gauteng is reported to be the most populous province of the country, much of the close-to-the-customer reference and therefore some of the supply and distributions are destined here (Melembe et al., 2020). Although, commercial small-scale farmers struggles are common countrywide, Gauteng-based farmers may be more fortunate in this instance. South African fresh produce distributing channels include FPMs, export channels and direct sales to wholesalers, retailers, hawkers, processors, institutional buyers and consumers. Interestingly, some of the produce for smallholder famers is held back for producers' own consumption. According to Louw and Jordaan (2018), the choice of distribution channel is influenced by the type and nature of the produce. However, according to the findings generated from the primary source data in the present study, the choice of distribution channel is also determined by the type of contract farming that the farmers have (those in possession of a GLOBALG.A.P. certification can access better markets or even take a shorter route along the supply chain process to reach the consumer). In the Gauteng Province, FPMs (48%) were the largest markets for smallholder farmers, which supports the findings obtained from the primary source data in this present study. Direct informal trade sales (farm-gate sales) and own consumption comprised the second-best channel at 42% of the fresh produce distributed (Figure 3.13) (DAFF, 2011). This contradicts to the findings obtained from primary data sources in this study, which revealed much lower fresh produce portions being sold at farm-gate or used for own consumption. The exports and processors contributed 3% and 7% of the fresh produce distributed respectively.

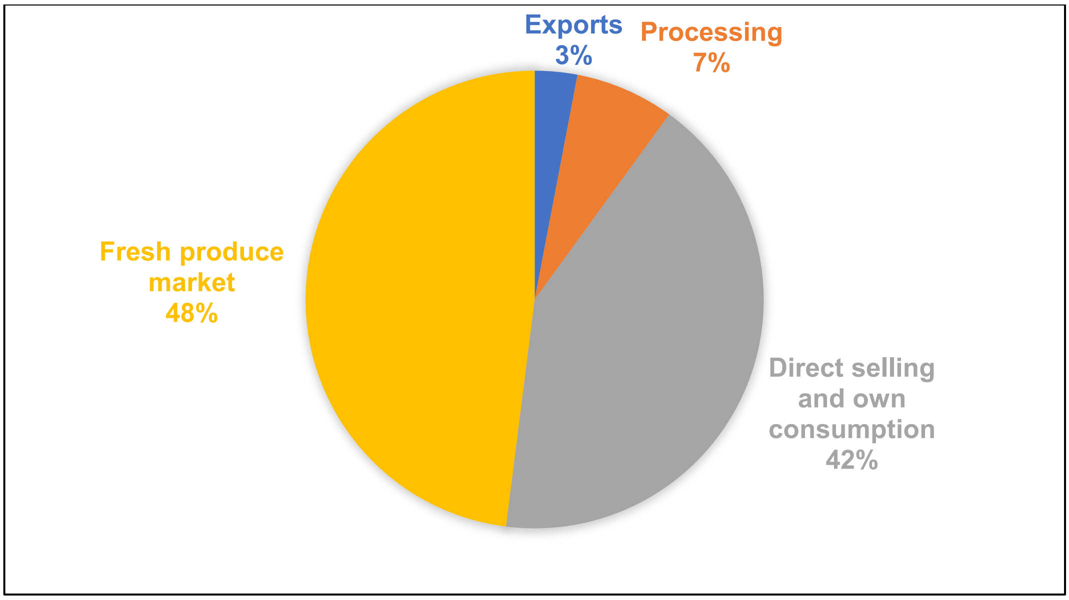

Figure 3.13: Distribution of fresh vegetable sales in Gauteng Province as reported by Louw and Jordaan (2018).

Local informal channels include sales to hawkers (62%) and farm-gate to local consumers (52%) (Figure 3.14) (Louw and Jordaan, 2018). The formal market through the FPMs has shown a significant decline from 48% in 2011 to 39% in 2018 financial year (Figure 3.14). This observation suggests that the number of smallholder farmers interested in participating in the formal market is declining. In contrast, the informal market participation is attracting more smallholder farmers. However, it is common that the informal market channel is associated with low prices, low to non-profitability and ultimate slow income generation. Dube et al. (2018) reports that the informal market is easily accessible because marketing costs (direct marketing) are relatively low and there are low value-adding requirements such as grading, packaging, and labelling. In most instances, there are zero transport charges because the trading happens at the farm-gate. Furthermore, informal markets offer more security because payments are instant, unlike in other channels where you get payments days or even weeks after delivering the produce. It is worse in case of the FPMs where payments may not be made due to inability to sell the produce until it loses its value.

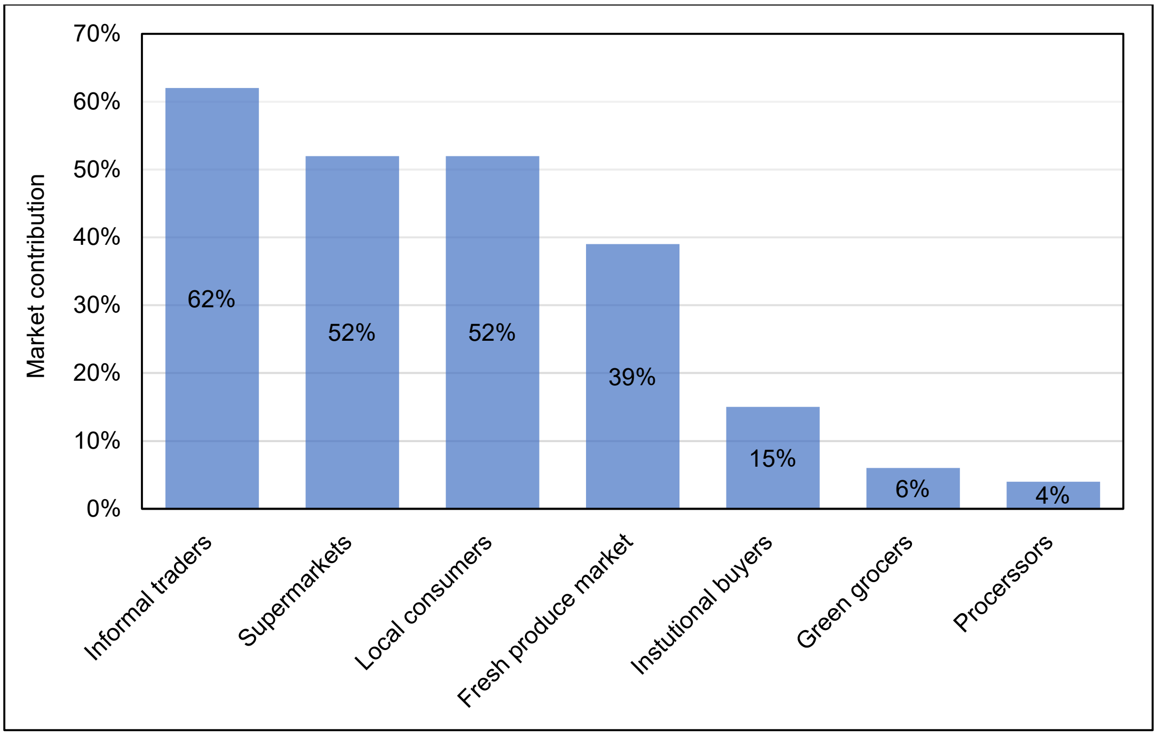

Figure 3.14: Fresh produce distribution for smallholder farmers in Gauteng Province for the season 2016/17 (adapted from Louw and Jordaan, 2018).

Agricultural supply chain and distribution is a complex process associated with great risk for smallholder famers (Figure 3.15). Some of the major risks that are encountered by smallholder farmers include low production yields, lack of post-harvest technology facilities; climate-controlled mode of transport, inability to access markets with consistency, yield variability and fresh produce losses. Management of these risks remains one of the major drawbacks for smallholder farmers to make it into large commercial operations. Ideally, farmers are keen to participate in the formal market such as retailers and institutional markets. Such markets require strict production regulations that comply with the GLOBALG.A.P. certification. This is a private certificate that can help farmers' competitiveness in high-value retail markets such as Shoprite, Pick n Pay, Spar and Woolworths. For instance, Johan Joubert, owner of Graceland Hydroponics, has indicated that despite producing high quality cucumbers he could not access these retail stores until acquiring GLOBALG.A.P. He reported that acquiring this certificate has helped Graceland Hydroponics to conform with global production standards daily norms (GLOBALG.A.P., 2015). South African vegetable industry generally struggle to export produce, despite strong export abilities in the fruit industry. Therefore, oversupply in to one market gets the prices depressed, so there is a need for industry growth and market expansion (Farmer's Weekly, 2018). The expansion would be ideal when starting with African neighbouring countries. Hence, recently it has been reported that Southern African Development Community (SADC) countries are the largest importers of South African vegetable products, primarily because they have retail outlets.

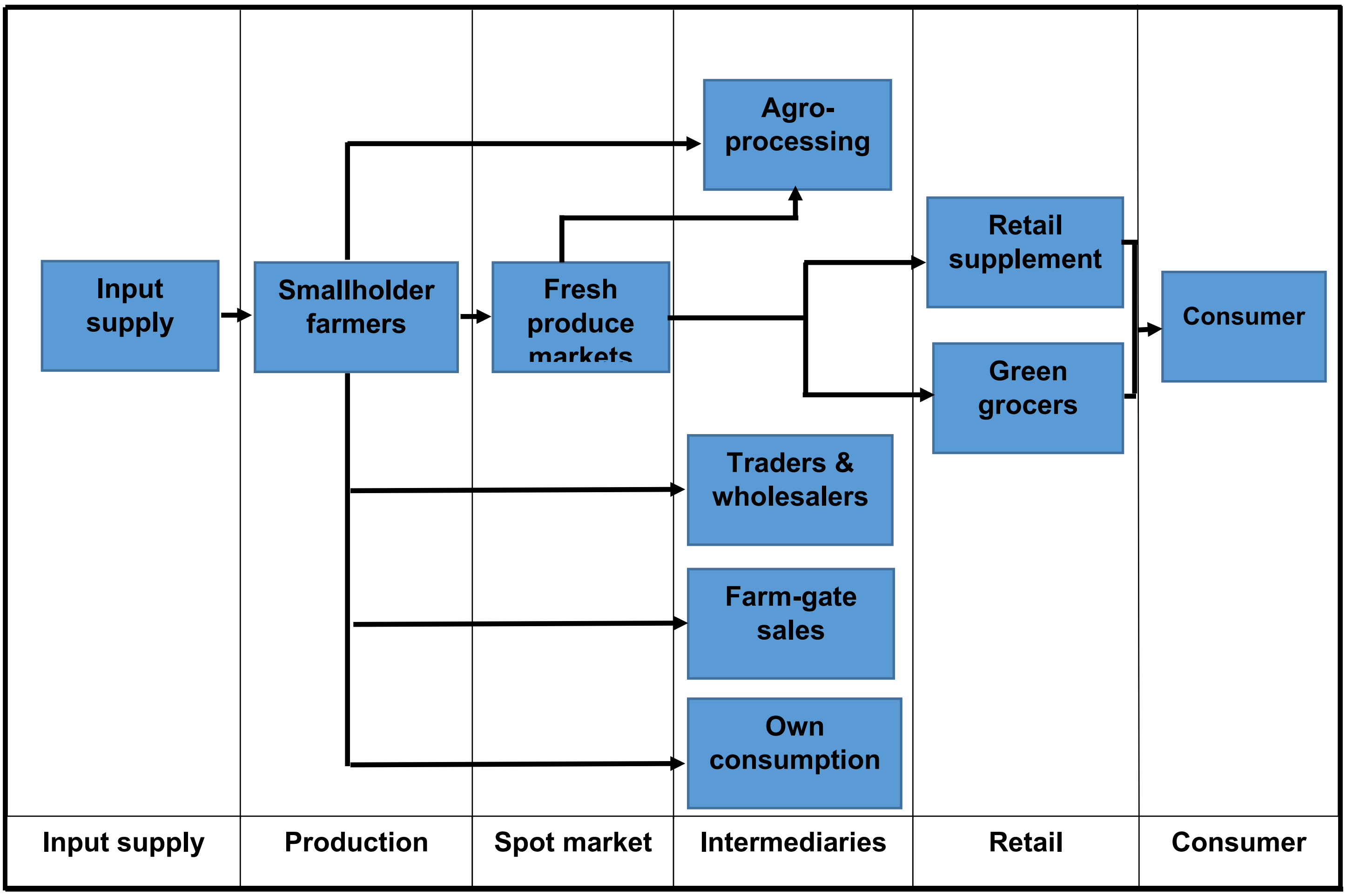

Figure 3.15: A generic diagram of smallholder fresh produce supply chain in the Gauteng Province of South Africa (adapted from Louw and Jordaan, 2018).

3.7 Fresh produce value-adding technologies

Value-addition is the alteration of fresh and raw produce into better value product for high economic returns (Dube et al., 2018). It can be done using sophisticated technologies and machineries or can be as simple as washing and packaging. Value-addition indicators are inclusive of postharvest activities and product development practices. Value-addition can also occur without tampering with the product's physical shape (Thindisa, 2014). However, it is important to note the difference between postharvest value-addition activities and agro-processing since they are used often, synonymously because they both add value. Agro-processing is a total transformation of the commodity, as it involves complex processes and expensive equipment (for example tomato processed into tomato sauce), whereas postharvest value-addition activities can be as simple and practical, like washing, packaging, cleaning, labelling, branding and sorting (Dube et al., 2018).

3.7.1 Packaging of fresh produce

Packaging fresh produce forms part of crucial steps of the produce value chain to the consumer. Packing and packaging materials are also an important aspect influencing the cost of the produce. It is important for growers to be aware of wide range of packaging options available. It plays an important role for consumer attraction and influences consumer preferences and acceptability. It further influences the expected shelf life, safety and the pricing of the produce. Packaging is important for the fresh produce protection and identification. For instance, the package must identify and provide useful information about the product/produce such as name, brand, size, grade, variety and net weight of the produce. In terms of protection, the package must protect the produce from mechanical damage and poor environmental conditions for a successful handling and distribution. This helps to avoid torn, dents and injuries on the produce. However, IDTT (2018) reported that there are some Small Medium and Micro-Enterprises (SMMEs) at the FPMs that educate farmers on the basic materials and advantages of packaging for specified commodities. Melembe et al. (2020) has indicated that smallholder farmers in Gauteng are aware of the packaging materials and how they can be used to enhance produce marketability. However, it was also noted that the price of the materials is a quite high. In addition, the extra labour charges and lack of storage facilities are other drawbacks for smallholder farmers. Packaging materials such as plastic bags (polyethylene film) are the most used materials by smallholder farmers because they are affordable, easily available and easy to use (Melembe et al., 2020). Although they are cheap materials, they still add much sought value to the produce (Dube et al., 2018). In the counterparts, large commercial farmers use modern produce packaging technologies such as modified atmosphere packaging and the use of edible coatings which contain antimicrobial compounds on the freshly cut produce. In addition, they use automated bagging machines, which further reduce packaging costs. Louw and Jordaan (2018) noted that these are some of the factors that continue to increase the gap between smallholder farmers and large commercial farmers. Hence, there is a need for re-formulation of policies at the national level to expand financial support programs for smallholder farmers, so that they can be able to acquire the relevant production and market technologies to become more competitive and successful.

3.7.2 Product development

Product developments of fresh produce are done through the agro-processing factories in South Africa. Normally, products developed from fresh produce vegetables include sauces, canning, spices and dressings. South African fresh produce is generally sold and consumed fresh. For instance, only about 10% of the fresh produce is processed compared to 50% in the United States of America (IDTT, 2018). The implementation of this involves expensive machinery, complex processes and knowledgeable personnel to handle the manufacturing activities. Smallholder farmers participate by securing contracts to supply fresh produce to SMMEs and large agro-processing companies such as Tiger Brands, Rhodes Pioneer Foods, Food Corp, Oceana Group, First SA Foods, Nestle, and Clover SA, which own about 70% of the industry (IDTT, 2018). Despite limited market shares, SMMEs play an important role to ensure a dynamic food processing environment in South Africa. These companies depend on formal retail chains to sell their manufactured products. This helps smallholder famers' participation in the agro-processing industry. However, more recently (Farmers Weekly, 2018), Ezra Steenkamp (the Deputy Director of International Trade Research at the Department of Agriculture, Forestry and Fisheries) indicated that, Asia has a fast-growing middle class and South African vegetable exporters are gradually responding to this demand by exporting processed foods to destinations such as Hong Kong, Singapore, Malaysia and Indonesia. These market destinations are currently accessible to South African based producers and have fewer phytosanitary requirements than other export destinations.

3.8 Guidelines on contract farming

3.8.1 An introduction to GLOBALG.A.P. certification

GLOBALG.A.P. is an international and private initiative that is responsible for standardised agricultural food production. The standards are set to promote good practices employed during food production. It was initiated by the European retailers after receiving alarming consumer concerns over food safety. Thus, the focus of GLOBALG.A.P. is on food safety and traceability, although it also includes some requirements on workers safety, health, welfare and conservation of the environment. The initiative uses handful inspection and certification as a tool to ensure requirements compliance. It has helped producers to comply with acceptable food safety, sustainable production methods, worker and animal welfare, and responsible use of water, compound feed and plant propagation materials. Although acquiring the certification is quiet a handful job, there are wide range of benefits that come along with the certification. The benefits include market accessibility, confidence to compete globally, improve the efficiency of farm processes and receive a GLOBALG.A.P. Number (GGN) for easy identification and traceability.

3.8.1.1 GLOBALG.A.P. compliance criteria

The GLOBALG.A.P. certification for vegetable standards starts from all activities involved in pre-harvest to postharvest activities. South Africa was listed the third country in Africa having the highest number of certified producers (2318), after Madagascar and Kenya (GLOBALG.A.P, 2018). The registration and annual fee for acquisition of the GLOBALG.A.P. are €100 (R1789,50) per hectare on production area, whereas nonproduction area cost €25 (R447,37). These costs are displayed on the GLOBALG.A.P. website for the 2020 financial year. The cost of the registration may be more or less depending on the agency that facilitates the inspection and certification process. GLOBALG.A.P. has got agents in different countries who are responsible for these certifications. Farmers can only get the necessary information and steps for the process of certification and thereafter choose company agents of their choice to start the process from inspection to certification. The following five steps are required to acquire the GLOBALG.A.P. certificate:

1) Download the relevant GLOBALG.A.P. Standard documents and checklists from the GLOBALG.A.P official website;
2) Evaluate site-specific available agencies and register with the most preferred one to get the GLOBALG.A.P. Number (GGN);
3) Conduct a self-assessment task using the checklist and adjust areas where the minimum requirements are not met to comply with a GLOBALG.A.P. A licensed Farm assurer, who is a trained and approved consultant, can provide valuable assistance during the audit preparations;
4) When ready for inspection, arrange an appointment with the GLOBALG.A.P. approved certification agency. An inspector will then come to do independent on-site inspection;
5) Lastly, once successfully passed the inspection and compliance with the standard requirements, a GLOBALG.A.P certificate is handed-out to the farmer (an Integrated Farm Assurance Standard certificate for the relevant version and scope, which is valid for one year). The waiting period for certification can range from several weeks to

several months depending on the farm condition and the agency chosen. Table 3.12 lists Certification bodies with branches in South Africa.

Table 3.12: GLOBALG.A.P. certification bodies (CB) with branches in South Africa (DAFF, 2012).

Company	Subcontracted CB	Contact details
Control Union Certifications South Africa	Control Union Certifications B.V	Johannesburg Tel: 0027 760365951 Werner Euler weuler@controlunion.com
Ecocert-Afrisco Pty Ltd	ECOCERT SA	Ecocert-Afrisco Pty Ltd Room 113 A Building 19 A CSIR Campus Meiring Naudé Rd Pretoria 0040 P.O. Box 74192 Lynnwood Ridge 0040 Tel: 123491070 Fax: 865180107 Vincent Morel office.southafrica@ecocert.com

3.9 Urban agriculture

Urban agriculture is a worldwide developing trend and it is largely driven by resource scarcity, urbanization, consumer preferences for locally and sustainably produced food and minimization of waste. In addition to its environmental benefits, the development of urban agriculture also creates job opportunities in urban areas and can contribute to food security. Commercially sustainable urban agriculture in South Africa is still in its infancy. Due to economies of scale, urban agriculture cannot sustainably compete with established large-scale farmers (Kuschke, 2020).

3.9.1 Urbanization and food security

As mentioned earlier, Gauteng is experiencing an increase in population due to the migration of people from other Provinces, which are less economically developed. Increasing urbanization will continue to create more opportunities for urban agriculture as a means to feed urban populations with locally and sustainably produced food. An increase in agricultural activities by households in urban areas would likely reduce the amount of households experiencing hunger by up to 60% (because 60% of households who reported experiencing hunger were in urban areas). This is particularly true in Gauteng, which has the lowest proportion of households involved in agricultural activities. An increase in Gauteng's household agricultural activities through urban agriculture would likely decrease the amount of households who report hunger as these urban poor households would be feeding themselves through subsistence farming similar to rural poor households in other Provinces.

3.9.2 Land use and employment in agriculture

As mentioned in earlier sections, Gauteng is the smallest Province by land size. It has the least number of farms and lowest farm employment. An increase in agricultural activities through urban agriculture in Gauteng Province would result in an increase the number of farms and employment within the province. This increase would have to be largely independent of land availability because this is inherently limited. This creates a good opportunity for urban agriculture, as intensive hydroponic farming solutions can be established in unused spaces such as rooftops and other areas that are not arable.

Conventional agriculture is generally perceived as a tough and outdated industry that requires migration out of urban areas for employment opportunities by young people. These perceptions hinder youth participation in the industry, hence limiting the industry's ability to create jobs for them (Strydom, 2018). Although agriculture is not a big employment sector, it tends to be a robust sector when it comes to withstanding economic pressures such as those created by a recession. Urban agriculture would likely behave in the same manner because growing urban populations need to be fed with increasing amounts of food regardless of the prevailing economic situation. This positions urban agriculture as a potential source of futuristic jobs in which the youth of today would be interested.

3.9.3 Water and climate change

As described earlier, climate change is a global concern and affects the agriculture sector in various ways. South Africa and Gauteng Province in particular, is a water scarce country. Thus, a farming solution that could increase the province agricultural activities without significantly increasing its water usage or demand could be an ideal solution to reduce hunger and increase employment within the province. Again, urban agriculture, when applied through hydroponics, aquaponics and aeroponics would be a sustainable way to increase food production in urban areas without significantly increasing the water requirements.

3.10 The state of hydroponics and urban farming in Gauteng Province

Commercially sustainable, urban-based hydroponics farming is a form of farming that can attract young people to the industry given its use of technology and location within urban areas. Hydroponics farming is not limited to arable land, which provides huge potential for integration into urban areas, where young people can participate. Due to several challenges encountered by the research team during implementation of this study, only farmers focusing on rooftop farming were interviewed. Three main organizations drive the rooftop urban agricultural movement in Gauteng:

- Urban Agricultural Initiative (UAI);
- Wouldn’t it be cool (WIBC);
- University of Johannesburg (UJ).

Johannesburg Inner City Partnership (JICP) developed the Urban Agricultural Initiative (UAI) with support from the City of Johannesburg, Department of Small Business Development, Small Enterprise Development Agency and SAB Kick start. Wouldn’t it be cool (WIBC) and University of Johannesburg (UJ) are also key stakeholders.

The UAI aims to create an urban agricultural ecosystem by repurposing disused rooftops to produce agricultural produce for Johannesburg’s inner-city communities. The initiative was established by the Johannesburg Inner City Partnership, in which Minerals Council South Africa is a key stakeholder. Mineral Council has funded and participated in a pilot project to assess the feasibility of growing herbs and other leafy greens on inner-city rooftops buildings including the Minerals Council itself. The first crop was planted on the Minerals Council rooftop building for the benefit of an Agripreneur, Kagiso Seleka. The Minerals Council hosted the launch of Urban Agricultural initiative on 11 October 2017.

The following key role players of the urban agricultural initiative were interviewed:

- Dr Naude Melan (UAI and UJ representative)
- Brendon Martens (UAI representative)
- Dr Michael Magondo (WIBC representative)
- Mrs Nickey Janse van Rensburg (UAI and UJ representative)
- Mrs Zandile Khumalo (Urban Farmer)
- Mrs Sibongile Cele (Urban Farmer)

3.10.1 Summarised notes from interviews conducted

3.10.1.1 Dr Naude Malan interview notes

Dr Naude Malan was interviewed on 08/09/2020. He is a lecturer at the University of Johannesburg and is a key stakeholder in UAI and Izindaba Zokudla which is a community based project that draws on multi-stakeholder engagements and action research methods to create opportunities of urban agriculture in a sustainable food system. It links the university, researchers, students, communities, entrepreneurs and other stakeholders in the development of service-learning and applied research projects and enterprises that can contribute to a socially equitable, economically productive and ecologically sound food system.

Izindaba Zokudla has enabled many emergent enterprises to thrive as new products and activities were developed amongst key stakeholders like the Khula App available on the Google play store. Izindaba Zokudla has influenced submissions to parliament. (https://acbio.org.za/en/seed-capture-south-africa-threat-seed-freedom-seedmovement-fighting-back) , established seed libraries like the Slow Food Ark of Taste's African Rainbow Maize Revival Project (https://www.slowfood.com/presidia-southafrica-rainbow-maize-rex-union-orange/) and other initiatives. It has collaborated with the NGO Slow Food to organize the Soweto Eat-In (since 2016) that show cases the best in heritage and indigenous foods. It has also organized the 'School Garden Dialogues' with Educators in Soweto, the iZindaba iLanga energy workshops with the Process, Energy, and Environment Technology Station (UJPEETS) on UL's Doornfontein Campus and other singular events that aims at entry by emergent food entrepreneurs into a sustainable food system in South Africa.

Dr Malan on urban hydroponic farms:
"A successful hydroponics system should be positioned to build the agriculture base of the entry level farmers who are currently experiencing a high failure rate. The development of "Circular Enterprises" around hydroponics holds potential."

Figure 3.16: Urban Vertical Rooftop Farm in Johannesburg (21/10/2020)

Major challenges reported included:

- Wholesale and retail markets are not suitable for small-scale farmers including rooftop farmers. A typical example is that carrot famers are paid R0.20 per kg delivered at the market (R0.10 farm gate price) when retail is around R40 per kg.
- If the project is solely funded by a 3rd party the entrepreneur does not have enough stake in the project to guarantee its success. The rooftop farmers must contribute equity capital and be economically and emotionally invested in the success of the farm. The entrepreneur has to be put through a holistic training solution (technical, business and stewardship) over and above their equity contribution.

The following recommendations were made for a successful hydroponics project:

- The recruitment system needs to attract the right kind of people. Ensure that the recruited people have stewardship of the project;
- The hydroponics farm must plant and sell high-value crops like herbs. As an example, purple basil can be sold direct to a high-paying customer;

- Light agro-processing in close proximity to hydroponic farm. For example, a hydroponic urban enterprise producing basil can convert the raw basil into a pesto before selling it to a direct high-paying customer. The basil pesto per kg would sell for R200-R300.
- Multi-coloured spinach, heirloom tomatoes are other examples of high-value crops with good potential for hydroponics;
- Abandoned buildings are not easily convertible into urban farms because of the natural lighting requirement in an attempt to avoid high electricity costs of LED grow light. It is also costly because converting these buildings requires specialised architecture. You will need to look at multi-use solution for entire building where lower floors become packaging and processing centres. Targeting unused warehouses where the roof can be replaced with natural lighting is a more sustainable approach;
- In order to make profits in hydroponics, only high-value crops must be sold. High-value crops include the following: fancy lettuce*,* purple basil (one step above basil), special variety herbs, multi-coloured spinach and baby spinach*,* heirloom tomatoes;
- Consistent electricity and clean reliable water supply are critical components, which sometimes are not available. Eskom is not reliable with its supply;
- Consistent water quality is required or a water cleaning system is needed.

The following potential solutions were pointed out:

- Potentially create a marketing co-op under a standardised branded growing system. Create production standards for farmers to ensure consistent produce quality, then market and sell the produce under the same brand;
- Decentralised farming operators are key in eliminating transport costs and must supply direct to restaurants;
- Izindaba Zokudla Farmer's Lab is used as a marketing platform;
- In the township, the fresh produce must be supplied directly to consumer markets, such as school feeding schemes, churches and weddings. Cleveland in America have pioneered the art of circulating money within the community, therefore a similar approach should be adopted;
- Investment in development of downstream agro processing (light industrialization) by packaging the products (vacuum packing to improve shelf life for the restaurants market), thus adding value.

Additional notes:

- People are very slow to take up hydroponics because the setup costs are prohibitive. Knowledge barrier is not a major problem because there are a few technical variables to consider, namely pH and EC. The cost of current solutions is prohibitive and there is room in the market for cost-effective solutions that reduce the cost hurdle currently presented by existing systems;
- In order for hydroponics farmers to better their chances of success, they have to be taught/mentored holistically (business skills and farming training);
- They need to be taught how to build a circular enterprise, i.e. how to repurpose farming waste to create an additional revenue streams.
- Small-scale township and urban farmers should not supply supermarkets or the Fresh Produce Markets because the price per kilogram is very low, thus reducing the farmer's margins;
- GrowPod Systems (a form of small-scale deep water culture hydroponic system that is irrigated manually and does not require any mechanical parts) are the cheapest systems on the market but are only ideal for small scale and subsistence farming. Commercial scale farming requires systems such as the Nutrient Film Technique (NFT). The knowledge requirements for a sustainable hydroponics operation is independent of production scale.
- City of Johannesburg's intention is to convert abandoned buildings into growing zones.

3.10.1.2 Mr. Brendon Martens interview notes

Brendon Martens was interviewed on 18/09/2020. He is the Chief Executive Officer (CEO) of Urban Agricultural Initiative (UAI). The UAI is a non-profit social enterprise that works to develop urban agricultural activities. This is achieved through enabling small-scale farmers to make use of advanced technology in farming. The UAI does not directly fund any urban agriculture projects. UAI sources funding from the Department of Small Business Development (DSBD).

Currently, UAI has 10 rooftop farms in the city of Johannesburg (Figure 3.17). Each farm is 250 square metre in size. The capital cost for each farm is R350 000. Each farm has a capacity of NFT systems with about 4000 planting spaces for leafy greens such as herbs and lettuce. UAI plans to build a further 40 rooftop farms in the near future.

Figure 3.17: NFT A-Frame Rooftop Farm growing Lettuce in Johannesburg (21/10/2020).

Major problems mentioned:

- Hydroponic projects are capital intensive;
- Commercial imperative vs social imperative – operations need to be established in an economically sustainable manner. Intensive hydroponic growing techniques cannot be used to grow low-value crops. Low-value crops are not economically sustainable with current technology costs;
- The cost of water is high and the quality varies;
- Nutrient Film Technique requires consistent supply of electricity so that plants can have a consistent supply of water and nutrients. This is a challenge due to Eskom load shedding and municipal power cuts;
- Rental cost of rooftops is high;
- Hydroponics farms cannot compete with conventional farmers. The cost of production for conventional farmers is low. This implies that produce can be sold at a lower price. Therefore, hydroponic farms are only suitable for high-value crops.

Potential solutions identified:

- Vertical farming to reduce the cost of production per square metre, increasing planting density to reduce rental cost per plant;
- Considering systems like Deep Water Culture to mitigate power cuts.

Hydroponic farm success drivers:

- The system should have some modularity to it;
- The Capital Expenditure (CAPEX) per planting space is a critical consideration;
- Operational cost of the system determines sustainability because farmers are price takers;
- Determine the appropriate farm size considering economies of scale, setup and operational costs like rent to ensure that farmers get a return on investment (ROI);
- Farm needs a complete system around it to succeed (i.e. inputs, logistics, packaging, market access);
- Customers (high-end restaurants and hotels) who will pay a premium for high quality produce. For example, R40 for a head of lettuce at restaurants vs R10 a head of lettuce at big retailers.

Additional notes:

- Urban farms must be close to or at a restaurant in order to be profitable (reduce food travel cost);
- High-value crops include: baby spinach, herbs and bespoke offerings such as living lettuce;
- Agro-processing is not a deal breaker; it depends on the target market. Restaurants do not require their produce to be processed but retail chain stores do;
- Different Living Standard Measure (LSM) groups have different food needs: (1) LSM 1-5 has food security problems. They require low value staple food; (2) LSM 6-10 has no food security problems. They seek healthy food and mostly high value crops.

3.10.1.3 Dr. Michael Magondo interview notes

Dr. Michael Magondo was interviewed on 23/092020. He forms part of a company called Wouldn't it Be Cool (WIBC), which is a business incubator and urban agriculture is one of their key focus areas. Johannesburg Inner City Partnership, an institution that aims to facilitate growth and transformation for all Inner-City stakeholders through collaborations with City of Johannesburg, approached WIBC to find a solution for food insecurity within the inner city. Currently, there are 22 farms built in the inner city with plans to roll out 130 farms in Johannesburg and Pretoria. WIBC is funded by National Treasury and other funders.

Figure 3.18: Typical Urban Rooftop Farm in Johannesburg funded by WIBC (21/102020).

Figure 3.19: Rooftop Farm in Johannesburg growing Lettuce (21/10/2020).

Figure 3.20: Rooftop Farm in Johannesburg growing basil (21/10/2020).

Major problems:

- Value chain structural issues – currently, the value chain does not support participation of small urban farming. Concentration is mainly on commercial farmers or farmers with a large scale operation;
- Misalignment between funders and project realities – there is an expectation of farming projects to be a job creation intensive industry through these urban hydroponics projects, instead of profitable sustainable enterprises irrespective of number of jobs created. Funders expect farming projects to create a large number of jobs per project, this is largely true for conventional farming projects but isn't for urban hydroponics projects. Success should be measured in terms of the number profitable and

sustainable enterprises created irrespective of the number of jobs created because hydroponics by nature is not labour intensive compared to conventional farming methods;

- Density and Diversity (in relation to hydroponics farms themselves) – High plant density to justify rental cost (of land) in urban areas;
- WIBC currently has a capacity of 3500 plants in a 200 square metre farm on their farms. This translates to a planting density of 17 plants per square metre. Planting densities below 20 plants per square metre threaten the profitability of the farm. Ideal plant density is 30 per square metre. This is based on the current NFT hydroponics system.
- NFT systems are affected by power outages since they require continuous flow of water through the system (that is only achieved through continuous availability of electricity to pump water to the system).
- Low planting densities and a poor market penetration for some of the crops produced have led to 4 urban rooftop farms being financially rescued and operations restructured.

Potential solutions

- WIBC is currently working with UJ to make solar energy available, but taking into account the cost of infrastructure involved. If solar energy integration would result in less than 5% increase in setup costs, it would financially justify its integration into the hydroponic systems;
- There is potential value in using a growing medium to offset the electricity outages but the cost of that introduction is too high;
- Hydroponics systems have significantly reduced the usage of electricity and water any further reduction in these two parameters would not be significant;
- Planting a wide range of high value crops can counter the financial problems that comes with low planting density (e.g. a system that can plant a combination of heirloom tomatoes and might make you more money than any hydroponics system that can only plant lettuce.

Hydroponics farm success drivers

- High-value crops like berries and hops. Hops are usually grown through a Dutch bucket hydroponics system (moving into high value crops will force a move from NFT to other systems, which will decrease the planting density);

- Other high-value crops include peppers, chillies, essential oils and micro greens which have value adding potential (agro-processing) and micro greens (e.g. baby spinach and watercress);
- Hop production is currently geographically constrained to environments that are ideal to grow it like in George, so through hydroponics the environment can be altered so that they can be grown anywhere. Import replacement is highly profitable;
- NFT system is a better compromise of the other systems for lettuce. So systems that can increase the yield or panting density will be good;
- Dealing with the market directly to increase price per kg for crops (selling direct to consumer);
- Direct to consumer online sales channels like Mila Fresh online store aimed to connect farmers with consumers are beneficial;
- Full ecosystem approach (stimulation support) is required to bring down the average investment per project;
- Total investment cost per job created is an essential metric for funders;
- Beneficiary sourcing program that removes barriers to entry and includes intense upskilling/training is required;
- Less than two hours of electricity outage is manageable;
- Reduction or elimination of transportation costs is important;
- Additional electricity savings to current setups are challenged by the Law of Diminishing Returns as a reduction of 50% in current operation leads to about R700pm saving;
- If diversity is achieved for the right high value crops density can be reduced;
- WIBC has removed structural barriers to entry (i.e. prior qualifications and experience requirements) and invested in building skills of potential farmers through their training program.

Additional notes

- WIBC Farms are profitable mainly due to market relationships and prices they are able to get, not necessarily on capacity and planting density of the plants. WIBC farms use natural lighting, shade netting and plastic tunnels (low-cost setup) fitted with NFT systems and negotiation of better rates for rental (low operational expenses);
- Living lettuce head goes for R5 per kg at the Johannesburg Fresh Produce Market (City Deep) and at 15 plants per square metre density, the cost per kilogram is R4.50 (landed at the market). Meaning the system only makes R7 per square metre. At 4 weeks growing cycle (per 200 square metre tunnel) this results in a yield of 3200 plants

(shrinkage is around 400 plants) (R0,50 per plant profit) which translates to about R1600 monthly profit;

- Cost of electricity and water amounts to about R1500-R1700 per month, which is low.
- Transportation costs minimal for urban hydroponics systems because of proximity to market;
- CAPEX for each rooftop farm is ca. R350 000 which suggests an ROI of 5.5%;
- The biggest operational costs for these urban rooftop farms are labour (for planting, harvesting and operating the system) and rental expenses;
- WIBC beneficiaries have a 0% interest loan on their farms;
- A monthly profit of R3000-R3300 would result in a return-on-capital of about 1%, which starts to be attractive to funders. So, planting density will be the biggest driver of profitability on WIBC farms;
- The current frequency of power outage is around 2 hours which have no real impact on the plants themselves;
- Water availability is not a huge issue, as the systems are highly efficient in terms of water utilization, which reduce the water usage to a minimum.

3.10.1.4 Mrs. Nickey Janse van Rensburg interview notes

Nickey Janse van Rensburg, interviewed on 05/10/2020 is the station manager of the Process, Energy, and Environment Technology Station (UJPEETS). UJPEETs has collaborated with both WIBC and UAI in the urban agriculture movement. Among other things, they provide these two organizations with technical support. One of the issues being researched is the feasibility of integrating solar panels to these hydroponic rooftop farms to resolve production issues related to load shedding.

Major problems

- Economic viability of farming projects are not taken into account – Community based projects are not designed to operate as self-sufficient and profitable entities. Projects are approached from a beneficiary mind-set. As funding goes away, projects often collapse;
- Leasing agreements on rooftops need to be relooked from a cost perspective as well as clarity on who is responsible for which costs (e.g. utilities and maintenance). Rooftop maintenance accounts for about 30% of the building’s maintenance, so urban rooftop farms can take care of that;

- Eskom Load shedding is affecting production through electricity outages. Solar energy technology works but is often too expensive. Life cycle of the battery is a concern. Utility cost saving is a consideration.

Potential solutions

- Farm operators need to be treated as entrepreneurs instead of beneficiaries. Entrepreneurs must contribute some form of equity into the project. Time that entrepreneurs spend on the project must be valued;
- Solar energy technology works. A return on investment can be realized after 5 years of operation;
- Rainwater harvesting systems and creation of a circular systems with sustainable urban drainage;
- Potential use of grey water for hydroponic production of high-value flowers;
- A policy that provides rebates to buildings for converting their rooftops to green gardens would be beneficial to urban agriculture (Rebate on Carbon Tax);
- Ideal solar solution is a hybrid business model that includes solar panels with batteries the system would power the farm and sell excess energy to the building that houses the rooftop farm.

Hydroponic business success drivers

- Right people are critical. Find people who are already invested or interested in agriculture. Women tend to be better agents for change in the community, so women should be considered to run community-based projects. Balance between street smarts and personality;
- Farm operations based in schools should be independent of the school. There needs to be an independent co-operative that runs the farm full time. Children and teachers can participate in school food garden as seasonal labour. In public schools, the Department of Education and Social Development can fund such projects.

Additional notes

- Target market is largely dependent on farm location. Township based farms – Start by growing local food and selling locally then look into exporting food to urban areas over time (planting and selling high value crops). Access to market and logistics are critical;
- Keep money flowing in the local community. Consider circular economic models;
- Create an artificial value chain (Seedlings, energy, water, nutrients, logistics and selling) within the township. (consider economies of scale);

- Containerized farming is only ideal for growing mushrooms. Mushrooms grow in the dark so there is no need for artificial lighting. Use the container for advertising. Consider economies of scale (how many containers are required to make the business model viable?);
- There is an opportunity for continuous skills development. Farmers should have someone to consult with when they do not understand something. There needs to be a proper project handover process which involves training on operation and maintenance of systems as well as after sales support;
- Farmers should invest in proper record keeping (technical and business information)

3.10.1.5 Urban Farmer (Mrs. Zandile Khumalo) interview notes

Zandile Khumalo, interviewed on 22/09/2020, is a hydroponics farmer based at the Vaal University of Technology Southern Gauteng Science and Technology Park (VUTSGSTP) in Sebokeng. She is the founder of HyHarvest. She currently operates a 300 square metre tunnel with an A-frame NFT system. She works with Kaelo Ratau Moroke who is a hydroponic specialist. Together they also provide consultation to farmers and hydroponic system designers. They have consulted for WIBC and helped to establish WIBC's urban rooftop farms.

Figure 3.21: Zandile's Urban Farm in Vaal (22/09/2020).

Figure 3.22: Urban Farm in Vaal Growing "Fancy" Lettuce (22/09/2020).

Major problems

- Inconsistencies in water pH, EC and temperature result in inconsistent growth and quality of plants.
- Electricity needs to be available 24/7 to ensure constant hydration of roots. Electricity outages cause plants to wilt then die. Plants wilt affects the overall growth of the plants even when they don’t die.
- Maintenance costs – maintenance costs decrease the profitability of the system. A well-built system is critical and often overlooked.
- Transportation cost, markets are far from their farm.
- Input costs such as fertilizers, seedlings and labour are all high-cost drivers.

Potential solutions

- Automation for remote water monitoring is required.
- A solar system is being installed as an alternative source energy source. The solar system is designed power the pumps periodically (not enough capacity to take the farm completely off grid).
- Getting a horizontal table system (not a typical A-frame system) in order to ensure that plants get consistent sunlight. The table system can allow us to grow a wider variety of crops (vertical systems only allow farmers to grow crops that a short in height).

Hydroponic farm success drivers

- Ensure that all critical skills such as basic understanding of irrigation systems, plant production and marketing are available in-house;
- Cover the tunnel with shade netting for hail protection and temperature reduction;
- Have an in depth understanding of market needs;
- Land is leased from the university for free and electricity is paid by the university;
- Consider selling lettuce as living heads (lettuce that is packaged with its roots) instead of pillow packs. Pillow packs require refrigerated trucks to transport since they wilt quickly. Living heads increase product shelf life;
- Crop choice is not critical. What is more critical is access to market. The market will dictate which crop to plant;
- Study the market trends and plant accordingly. This will reduce the transportation costs and increase profits.

Additional notes

- The system currently has a capacity of 7200 herbs or 3600 heads of lettuce (lettuce are not closely spaced as herbs, hence the reduced number of plants);
- The challenge with planting lettuce is that there will be vacant planting spaces in between the plants. This will result in water being exposed to direct sunlight, which causes algae to develop.

3.10.1.6 Urban Farmer (Mrs. Sibongile Cele) interview notes

Mrs. Sibongile Cele, interviewed on 22/09/2020, got involved in agriculture through the field of Permaculture, Hydroponics, Aquaponics, Fish Breeding and Organic Farming. Her exposure and knowledge of agriculture came through her father who participated in communal farming. Her entity, Mcebo Unlimited Wealth, is registered as a social enterprise that she runs together with her husband. Her system is in Hillbrow on a crèche rooftop.

The rooftop farm is a 300 square metre, which has a total capacity of 3600 plants. The system is comprised of 6 NFT system of 600 planting spaces, each with its own independent irrigation system.

Figure 3.23: Sibongile Cele Urban Rooftop Farm in Johannesburg (26/09/2020).

Figure 3.24: Sibongile Cele Farm Interior in Johannesburg (26/09/2020).

Major problems

- Electricity outages:
    - Eskom loadshedding, crops usually die after 5 hours of power failure.
    - If there is no electricity, then algae start forming at the bottom of the tank as the water stops circulating which results in root rot.
    - The farm is operated on the rooftop of a crèche. Any outages which result from other residents in the building not paying electricity also affects her farming operation.
    - The worst outage Mrs Cele has experienced lasted for 2 full days. This outage was caused by the riots that occurred in the Johannesburg inner city. A diesel generator was another potential solution Mrs Cele considered for the electricity outage. However, a diesel generator makes a lot of noise when it is in

operation. This prevented her from using it because there is a crèche on the same building she is using its rooftop to farm.

- The tunnel experiences two extreme weather conditions (too hot or too cold)
    - The tunnels on the rooftop experience extreme variations in temperature conditions especially when there is a heat wave. This results in plants starting to wilt.
    - In the winter season, the temperature on the rooftop gets so low that the plants often experience frost damage.
- Water quality
    - Gauteng water is acidic (due to mining belt) and naturalization is important and costly. This results in a high spending on fertilizers and chemicals that are used to balance the pH.
    - The high acidity in the source water causes yellowing of leaves. This is primarily because plants grown in acidic water cant access some nutrients in the water.
    - The system requires constant monitoring to ensure that water pH and EC are within desired range. Mrs Cele has UJ students who do their experimental learning practical at the farm, they provide additional labour and often help with monitoring.
- The three tunnels are not separated; therefore all plants experience the same weather conditions and if there is an infestation of pests on one tunnel all crops will get affected.
- In hydroponics systems (especially A frame systems), one side of the farm experiences more sunlight than the other. Strategic placement of crops is important (i.e. place the plants that need more sunlight on the side that experiences to greatest sunlight)
- Installation costs for a solar system are high but return on investment (ROI) is eventually realized. It is advisable for aspirant farmers to start off with a system that has solar energy available, this will increase their chances of success and prevent loss of crops from the start.

Potential solutions

- Solar as an electricity substitute is feasible (depending on the affordability/pricing of renewable energy options). Generator is expensive and too noisy for a rooftop farm.
- Use shade netting on top of the greenhouse in order to protect the plastic tunnel from hailstorm. Shade nets also reduce the temperature inside of the plastic tunnel.
- Remote monitoring of the water and climate conditions in the greenhouse. (often too expensive)

Hydroponic farm success drivers

- Selling high value crops like herbs and edible flowers such as Nasturtium (Nasturtium is mainly used by caterers, hotels and restaurants);
- The Johannesburg Fresh Produce market is not an ideal market for emerging farmers because selling prices at the Fresh Produce Market are low. In addition, a commission of 12% in total is charged. 7.5% is paid to the market agents and the remaining 4.5% is paid to the Fresh Produce Market;
- Retail market such as chain stores (Pick N Pay, Checkers, Spar, etc.) are not a viable market for emerging farmers because prices are too low. They also take around 30 days to pay the farmer, which disturbs the cash flow of emerging farmers;
- An ideal market for emerging and small-scale farmers is a market that eliminates the middleman. This ensures that an emerging farmer can charge a higher price which will increase profit margins. Such markets pay cash on delivery and that maintains a good cash flow for the farmer. For example, a bunch of spinach was going for R10 (farm gate price) which it sells for R3 at the Johannesburg Fresh Produce Market in City Deep;
- Such markets include:
  - Aggregators – this includes street vendors and individuals who buy and sell to the community. Free agents that buy direct from the farmer, pay cash, pick up and sell to their identified communities;
  - Victoria Yard in Besville;
  - Wits Market at the Wits campus (in partnership with the food sovereignty department);
  - Jackson’s Real Food Market in Fourways;
  - Brownsense Market;
  - E-Commerce markets are Khula App and Urban Fresh;

Additional notes

- Biggest cost drivers are electricity, water, rent and labour;
- Electricity costs is R700 per month;
- Water costs is R500 per month;
- Rental cost is R2000 per month (biggest cost followed by labour);
- Extra manpower is required during harvest and planting period.

3.10.2 Summarized notes

Urban farms

Figure 3.25: Full Grown Leafy Lettuce (21/102020).

Major problems in urban hydroponic production

<u>Economic viability of projects</u>

- The current structure of existing food value chain is not conducive to small-scale farming operations such as rooftop farms. Wholesale and Retail Markets are not suitable for rooftop farms, direct to consumer sales avenues may be more sustainable, as long as contract agreements are put in place to protect the parties involved in business.
- There is a misalignment between funder's expectations and project realities; hydroponic projects are expected to be high job creation vehicles whereas they are not labour intensive by nature.

  - High capital and operational costs of rooftop farms, these costs limit the types of crops that can be grown profitably. Only high-value crops can be grown.
  - Low density (lower than 17 plants per square metre) and low diversity systems do not work because planting densities need to justify high rental costs in urban areas.
- Technical problems:
  - Lack of consistent electric supply due to load shedding and municipal power cuts.
  - Variable municipal water quality.

Major potential solutions

- Offsetting the need for increased planting density by using low density systems that enable planting high-value crops such as Hops.
- Negotiating better price per kg through creative marketing and sales avenues.
- Direct to consumer marketing.
- Solar energy integrated into urban farm.
- IOT water monitoring systems.

3.10.3 Current trends in hydroponic production

3.10.3.1 Prevalent Hydroponic Systems

Most rooftop-based farms use NFT systems, which are a good compromise (for growing leafy greens) within all systems currently available on the market. Dutch Bucket systems are also a good compromise for growing vine crops. Both WIBC and UAI are continually piloting other hydroponic systems and experimenting with different crops to determine the “best use” systems based on the desired production mix.

Rooftop farms are typically 200-300 square metre in size and covered with a combination of plastic or shade netting. Most systems are low tech and do not have automated climate, pH and EC monitoring systems, temperature control systems or automated irrigation control. Most systems still require a fair amount of labour due to lack of automation. Future Farms is the prevalent hydroponic systems installer on rooftops in Gauteng. They typically install 200-300 square metre NFT systems under plastic and shade netting. The hydroponic systems are mainly A-frame systems for leafy greens.

Dynatrade, Greener Solutions, Hytech Agriculture and Vegtech are all suppliers of hydroponic systems although their focus is mainly in peri-urban areas where larger systems can be built such as multispan greenhouses and large-scale shade net and tunnel production.

3.10.3.2 Crop types and market trends

Below is a list of crops that are on trend at the moment. The trend is highly influenced by the high price that these crops can be sold at. High-value crops are critical for the sustainability and profitability of hydroponics systems.

- Leafy “fancy” lettuce
- Living lettuce
- High value herbs
- Micro greens
- Edible flowers
- Multi-coloured spinach
- Baby spinach
- Heirloom tomatoes

Selling direct to consumers by eliminating any third party or middlemen increases the profitability and sustainability of the farm.

Such markets include:

- Various farmer’s markets (such as Vitoria Yard, and Jackson’s Real Food Market)
- Hotels and restaurants
- Catering companies
- Direct to consumer through E-commerce (such as Khula App, Urban Fresh and Mila Fresh online store)
- Township based markets include School feeding schemes, churches and events such as funerals and weddings.

Markets such as retail chains and Fresh Produce Markets are not ideal markets for small-scale farmers because of the low price per kg and high commission charged. Retail payment terms are also not ideal for small-scale farmers. A 30-day payment terms can cause cash flow problems.

3.10.3.4 Potential of value addition

- Invest in development of downstream agro-processing (light industrialization) by packaging the products (vacuum packing to improve shelf life for the retail market), thus adding value (ca. 200%) to it.
- Restaurants do not require their produce to be processed but retail chain stores do.

- A standardised branded growing system may be ideal. Decentralised operators supplying end-user markets – e.g. restaurant chains, create production standards for farmers to ensure consistent produce quality then market and sell produce under same brand.
- Reduce food travel time by planting close to restaurants (or on location)
- Containerized farming is ideal for growing mushrooms. Mushrooms grow in the dark so there is no need for artificial lighting. Use the container for advertising.
- Consider circular economic models.

3.11 Hydroponics in the context of WEF

3.11.1 Energy/Electricity

- Hydroponic farms (particularly low-tech systems) are design to operate with a low energy requirement.
- The cost of electricity is not a huge concern, but the consistency of electricity supply is. Electricity outages due to Eskom loadshedding and power cuts by municipality cause the following problems:
    - Inconsistency in produce quality and size. Electricity outages result in plants not having access to water and nutrients a certain period in a growing circle which will affect their growth (markets want consistency in supply and quality)
    - Loss of crops – Unavailability of water due to pump failure often result in crops dying in situations where there is no electricity for more than 3 hours.
- Solar energy can be used as backup power and/or off-grid solution, but setup costs are considerable while diesel generators affect profitability as the diesel price fluctuates. (Selling price does not fluctuate). Diesel generators also tend to be too loud to operate.

3.11.2 Water

- Hydroponic systems require close to 90% less water compared to conventional farming methods. (System leaks tend to reduce efficiencies)
- Rooftop systems use municipal water and not borehole water, as such the cost of water is an important variable. Cost of water is high when compared to cost of electricity in a rooftop farming operation.
- Access to water is usually not a problem.

- Inconsistency in municipal water quality tends to affect the quality and consistency of plants. Municipal water in Gauteng is either very acidic (low pH due to mining belt) or very alkaline (high pH).
- Constant monitoring of water quality is important and increases the labour burden but can be done easily through automation.
- Nutrient Film Technique requires consistent supply of electricity so that plants can have a consistent supply of water and nutrients.

3.11.3 Food

- Small-scale hydroponics farms cannot compete with conventional farms. The cost of production for conventional farmers is low due to economies of scale. This implies that produce can be sold at a lower price.
- Hydroponics is most likely to solve food security in urban areas when approached from a social motive as opposed to purely commercial motive. For example, supplying the urban poor with hydroponic systems to grow their own food as opposed to selling that food.
- Hydroponics is most likely going to add food choice to LSM 6-10
- Different Living Standard Measure (LSM) groups have different needs:
    - LSM 1-5 have food security problems. They require low value staple food produced by conventional farms at scale.
    - LSM 6-10 have no food security problems. They seek healthy food and mostly high value crops that are sustainably produced. Locally produced food is a consideration.

Hydroponics only has the potential to increase total available food for LSM 1-5 when it is a non-profit community based type of farm. Hydroponics has the potential sustainably increase the total available food available for LSM 6-10 and maintain profitability. This increase can be achieved without a major addition to the water, energy and land required to produce this food. As such, adoption of hydroponics for production for crops largely consumed in LSM 1-5 such as spinach is questionable without continued external funding from an organization that is aimed at community based farming. The adoption rate of hydroponics for production of crops consumed in LSM 6-10 will likely be higher due to its profitability. A good compromise to this problem is the setup of hydroponic production systems in the townships to export high value crops to the urban areas.

3.11.4 Market size

UAI has installed 10 rooftop farms and plans to install 40 in the near future. WIBC has installed a total of 22 roof top farms and plans to install 130, together they have plans to install a further 170 rooftop farms in the near future. A typical 200 square metre farm has an NFT A-Frame hydroponic setup with irrigation, installed under shade netting or plastic and costs R350 000. The potential future available market for urban rooftops hydroponic systems is currently as presented in Table 3.13.

Table 3.13: System market size.

Organization	Total planned Farms	Average Cost per 200 m^2 farm	Potential Future Market Size
UAI	40	R350 000	R14 000 000
WIBC	130	R350 000	R45 500 000
Total	170	R350 000	R59 500 000

Typically, each 200-300 square metre rooftop farm has about 4000 planting spaces. In the inner city of Johannesburg there are currently 10 UAI Farms and 22 WIBC farms. Monthly, the total maximum available leafy greens produced is 128 000 plants. This is a mixture of high value crops. The mixture varies from month to month depending on market requirements.

- Living lettuce head goes for R5 per kg at the Johannesburg Fresh Produce Market (City Deep) and at 15 plants per square metre density, the cost per kilogram is R4.50 (landed at the market). Meaning the system makes R7 per square metre. At 4 weeks growing cycle this results in a yield of 3200 plants (R0.50 per plant profit) which translates to about R1600 monthly profit.
- These calculations are based on the a shrinkage of around 400 plants, moving the monthly yield from 3600 to 3200 and on a summer growing circle of 4 weeks.
- The critical consideration for the successful urban hydroponic farm is density.

The total available market (per cycle) for rooftop hydroponically produced crops is as follows (Table 3.14):

- Assuming 4-week planting cycle and 10 cycles per annum
- Assuming living lettuce is sold at R5-10 per kg
- Assuming one head is 100 g (10 heads make a Kg)

Table 3.14: Total rooftop crop production market size.

Organiza-tion	Farms	Planting capacity	Selling Price	Total Expected Income (per cycle)	Total Expected Income (per annum)
UAI	10	40 000	R5-R10	R20 000-R40 000	R200 000-R400 000
WIBC	22	88 000	R5-R10	R44 000-R88 000	R440 000-R880 000
Future potential	170	680 000	R5-R10	R340 000-R680 000	R3 400 000-R6 800 000

The total expected income can be increased, by either increasing the planting capacity or seeking out and creating new sales channels that allow a higher price per kg.

3.11.5 Potential of hydroponics to solve economic and environmental challenges

3.11.5.1 Economic potential

- WIBC has removed any prior experience and qualification requirement to be part of their program.
- Potential beneficiaries undergo a training program to ensure that they have necessary skills to run the farms as a successful business.
- Job creation potential for young people in the city has been identified.
- Together WIBC and UAI have created jobs for at least 62 entrepreneurial farmers and plans are in place to increase that amount to 170.
- Potential to incorporate a circular economy business model that can integrate other entrepreneurs into the Rooftop farming eco-system has been identified. This includes incorporating e-bikes for last leg logistics, installing solar systems with the intention of allowing access electricity to flow back into the grid.
- Barriers to uptake of urban agriculture are:
  - Administrative environment is not enabling (zoning, water allocation and tariffs are prohibitive)
  - Business case issues (commercial vs social motives)
  - Lack of access to finance for hydroponic systems by established financial institutions
  - Access as to markets with offtake agreements.

3.11.5.2 Environmental potential

- Water harvesting – creation of a circular system with sustainable urban drainage.
- Potential for rooftop farms to reduce the heating and cooling load has been identified but the actual impact is still being investigated.

- Low Tech systems are just as vulnerable to climate change as conventional systems. They are especially vulnerable as they experience highly variable temperature conditions due to their height above ground. High Tech systems are not vulnerable as they control the climate conditions in a closed system, however the setup and operational costs of these systems are unsustainably high at low scale.

3.12 Conclusions and recommendations

This situational analysis study, based on a limited sample in the Gauteng Province of South Africa, confirmed the well-known and usual problems faced by hydroponic commercial farmers in this particular context. These farmers face several challenges at production and market access levels, of which the major ones include low crop productivity, lack of production infrastructure capacity, production inputs and sufficient knowledge of hydroponics production, limited access to markets and water supply, lack of financial support or government incentives, poor storage and transportation of fresh produce, lack of value-adding technologies and contract farming certification. The challenges can be addressed through knowledge dissemination and training of farmers for improved crop productivity (marketable yield and quality), appropriate record-keeping of production inputs, input costs, generated income and profits for easy evaluation of business sustainability, acquisition of GLOBAL G.A.P certification and adoption of value-adding technologies to increase farmers competitiveness in the market.

As of 2019, Gauteng Province is home to a population of 15.2 million people (25.8% of the country's population). This population is predicted to increase due to an increasing population and net immigration into Gauteng. According to Statistics SA, net immigration into Gauteng from 2006 to 2011 was estimated to be about 974 765 people. From 2011-2016 it was estimated to be about 1 026 451. Net immigration is projected to increase by 980 398 from 2016 to 2021. Gauteng is one of the richest provinces in South Africa, however it has the largest percentage of households (25.2%) that experienced hunger. This is due to the fact that, Gauteng has a much larger urban population and most of the households that reported to have experienced hunger are located in urban arears. In Gauteng 84% of households reported having adequate access to food and 12.9% inadequate and 3.1% severely inadequate. The province only accounted for 8% of households involved in agricultural activities. The smallest Province in terms of number of farms and farm employment was Gauteng (5.7% of farms and 4.8% of employment). The total amount land use in Gauteng as at 30 September 2018 is as follows: 385 317 (0.8% of total SA). Arable land is 180 349 (2.4%) Grazing land 197 878 (0.5%) other land is 7 088 (0.3%). Gauteng has limited local water resources and imports 88% of its water supply from various inter-basin transfer schemes that relies on a sophisticated water distribution system that receives water from 5 river basins across 6 Provinces. The climatic conditions that sustain these water sources variable, unpredictable and have a history of multi-year droughts. The need for hydroponics in urban environments was clearly articulated using rooftop farming as an example. Similarly, the potential for hydroponics to draw young people to agriculture was also identified. Hydroponics can also be used to increase the number of households involved in agricultural activities within Gauteng Province. Hydroponics is a sustainable way of producing food within urban environments, and it is a farming technic that inherently nested within the Water Energy Food nexus. Its lower water and energy requirements, higher planting densities per square metre and its potential to farm using non-arable land are all advantages that make it ideal to farm in a manner that keeps the WEF nexus in mind.

Gauteng has limited local water resources and imports 88% of its water supply from various inter-basin transfer schemes that relies on a sophisticated water distribution system that receives water from five river basins across six provinces

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Farmers are encouraged to increase the number of tunnels available for crop production, particularly those with temperature-controlled mechanisms to allow continuous crop production, market supply and income generation all-year-round. This is particularly crucial in the Gauteng Province of South Africa, due to the relatively cool weather conditions during the winter period. Renewable energy sources, such as solar- and wind-derived energy, are of utmost importance to hydroponic farmers to ensure continuous energy supply and systems operation. Several hydroponic farmers still lack appropriate skills for the operation and maintenance of hydroponic systems. As a result, there is a need for training and capacitation of farmers, in terms of optimum production practices, selection of suitable cultivars and promotion of value-adding technologies.

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CHAPTER 4: ON-FARM DESIGN, SET-UP, OPERATION AND TESTING OF THE HYDROPONICS PLANTER SYSTEM

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4.1 Introduction and background information

AB Farms was officially founded in January 2017, by two UJ graduate mechanical engineers. However, the concept was conceived in 2016 with exploration and initiation of the initial experimental site pictured below. We designed and built our own hydroponics model to broaden our understanding and further investigate the advantages and disadvantages of this technique. We built two growing systems that cultivate vine crops and leafy-type crops independently. These systems were placed under shade netting to keep large pests, hush winds, and hail away from crops (Figure 4.1).

- Our Dutch bucket system could grow vine crops such as tomatoes, cucumbers, peppers, etc. (10 plants per cycle).
- Our A-frame system could grow leafy vegetables such as lettuce, herbs, spinach (150 plants per cycle).

Our crops were irrigated automatically by an irrigation system that we developed. Water circulated through the system and was recycled back to the irrigation tank, where nutrients were checked and rebalanced daily to desired concentrations.
Below are pictures of the Dutch bucket system (growing tomatoes) and A-frame system (growing lettuce).

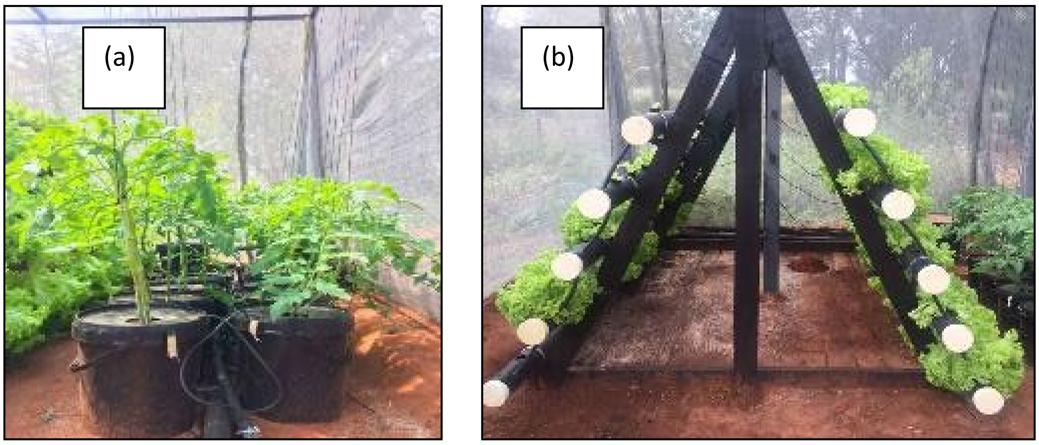

Figure 4.1: Dutch Bucket a); A Frame system b).

Data collected from these two systems assisted us in coming up with a vertical hydroponic planting unit that can be used for the production of leafy green crops using less water, land and energy. This planting unit is the subject of this project. The development of this planting unit was funded by Water Research Commission (WRC) through Water Technologies Demonstration Programme (Wader)

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This report summarizes the design and building process of this planting unit from finalization of product design specifications through to the testing and demonstrating of the product in its natural operation environment.

4.1.1 Problem statement

According to the United Nations, the current world population of 7.7 billion people is projected to grow to 8.5 billion people by 2030 and 9.7 billion people by 2050 (United Nations, 2019).
For 2019, Statistics South Africa (Stats SA) estimates the mid-year population at 58,78 million. Approximately 51,2% (approximately 30 million) of the population is female. Gauteng comprises the largest share of the South African population, with approximately 15,2 million people (25,8%) living in this province. KwaZulu-Natal is the province with the second largest population, with an estimated 11,3 million people (19,2%) living in this province. With a population of approximately 1,26 million people (2,2%), Northern Cape remains the province with the smallest share of the South African population. (Statistics South Africa, 2019)
The South African population is projected to grow to 66 million by 2030 and 75.5 million by 2050 (World Population Review, 2022).

This increasing population will need to be fed sustainably using finite land, energy and water resources. We at AB farms hypothesize that hydroponic technology will play a big role in insuring food security for an ever-increasing population.

All hydroponics pipe systems currently available on the market do not have a water storage capacity incorporated in their designs. Consequently, most systems require that water be flowing through them continuously. Therefore, irrigating systems have to run continuously, in order to prevent the plant roots from becoming dry thus hindering plant growth or killing the plant. While some designs have incorporated an inert medium in their usage, this medium is often not reusable thus increasing operational costs.

At a time when electricity in South Africa is becoming more expensive (753% increase from 2007 to 2021) (Moolman, 2021) and more unreliable due to power failures. Latest load shedding statistics released by the CSIR confirm a critically constrained South African power system with YTD 2021 energy not supplied exceeding 2020 levels, and with an increasing trajectory (CSIR, 2021).

It is becoming economically unsustainable to operate hydroponic systems continuously over extended periods of time. Particularly, during power failures, when generators have to stand in for conventional electricity. The wholesale cost of 0.005% diesel has increases from R10.33 per litre in January 2012 to R17.28 per litre in January 2022 (Sapia, 2022). This is an increase of 67.27% over the last 10 years.

We have, hence, designed a pipe system that allows the plant to have access to water continuously even though the irrigating system is off due to power shortages, pump failure or any other reason. The design essentially allows for plants to be irrigated periodically, as opposed to continuously, thus reducing the amount of energy required per kg produced. It also inherently saves water as all hydroponic systems do and Due to its vertical nature it achieves higher planting densities than traditional hydroponic systems.

4.1.2 Study aim and objectives

The aim of this project is to demonstrate our hydroponics planter system in its natural operating environment. In other words, our aim is to test the performance of the hydroponic planter placed in a standard 300 m^2 tunnel. We are testing the performance in terms of water, energy, fertilizer land usage per kilogram produced, quantity and quality of produced crop.

A standard 300 m^2 (10x30 m) plastic tunnel fitted with a temperature control system was installed at the Westonaria Agripark, under which our vertical hydroponic system of hydroponic planters is being operated.

The objectives were to determine;

- the amount of water used,
- the amount of energy used,
- the amount of fertilizer used,
- the yield per square metre of the system, and the quality of the produce (average weight per plant, total weight produced and marketable yield).
- the water use efficiency of the system

4.2 Research methodology

4.2.1 Description of study site

The demonstration site is placed at the Westonaria Agripark located in the West Rand District municipality. The site is located at portion 34 of the Gemspost with a total size of 10Ha and its coordinates are: -26.2785 Latitude and 27.6816 Longitude (Figure 4.2).

Figure 4.2: Westonaria Farmers Production Support Unit (FPSU) Aerial View.

Westonaria FPSU currently houses co-operatives and private companies that occupy different structures within the FPSU. The following structures, illustrated in Figure 4.2, are each occupied by a co-operative or private company:

- Twenty 300 m^2 greenhouses under drip irrigation (labelled 8).
- 300 m^2 vertical hydroponics chamber (labelled 6).
- 6000 m^2 shade net structure under drip irrigation (labelled 7).
- Seven 10 m^2 shade net structures under drip irrigation (labelled 9).

- 4 Hectare open field and 2 Hectare shade net under drip irrigation (labelled 10).

The Westonaria FPSU consist of other workspaces that are shared amongst the Co-operatives and private companies, these include:

- One borehole and municipal water connections.
- Three phase electricity provided by local municipality.
- A Pack house facility which consists of packing tables, wrapping machines, two cooling rooms complete with cooler unit and ablution facility (labelled 3).
- An office block with 100 square metre training/workshop centre (labelled 2).
- A Mechanization warehouse under construction (labelled 4).
- A ClearVu fence surrounding the entire site and one entrance gate with security guard house (labelled 1).

Access to the site is controlled and restricted by security and permission from resident companies is required before access can be granted to the general public. Surveillance cameras are installed to bolster security within the premises. AB Farms unit is illustrated in Figure 4.3.

Figure 4.3: AB Farms Pilot Site Location.

4.2.2 Hydroponic structure characteristics

A standard plastic tunnel fitted with a temperature control system was installed at the Westonaria Agripark, under which our vertical hydroponic system of up to 10 000 planters is being operated. The vertical hydroponic structure is 2.5 m high, 10 m in width and 27 m in length (Figures 4.4 to 4.7).

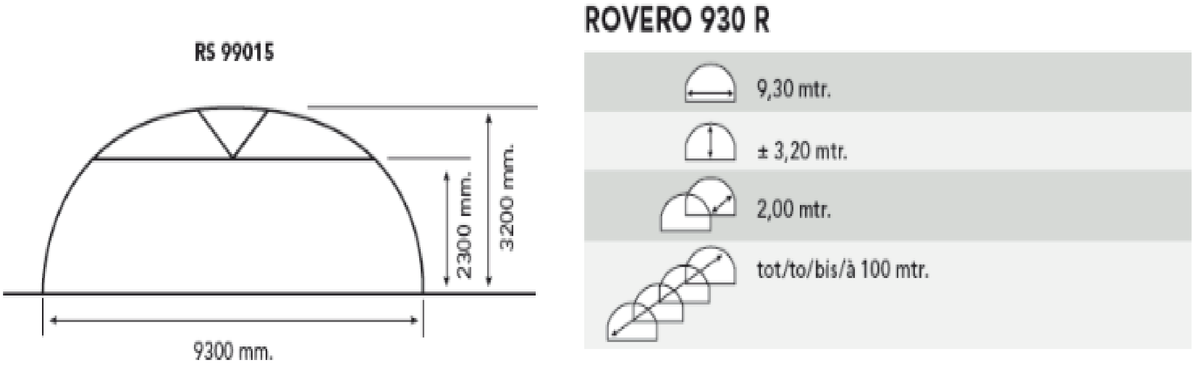

Figure 4.4: Tunnel Specifications.

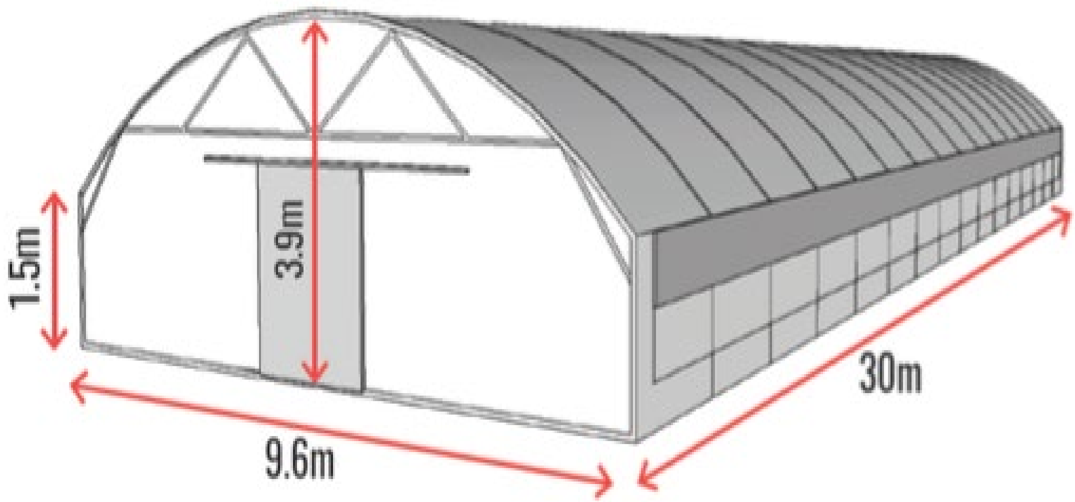

Figure 4.5: Tunnel Dimensions.

Figure 4.6: Front of Tunnel.

Figure 4.7: Back of Tunnel.

4.2.3 Hydroponic system design

The design of the hydroponic system functions as follows (Figure 4.8):

1. Fresh water is pumped from a water source (5000 l tank) into the underground catchment tank (2500 l).
2. Nutrients are mixed and administered manually to the catchment tank.
3. Water coolers regulate the catchment water temperature. (Optional)
4. Water is then pumped through a mechanical filter to the hydroponic planters, irrigation is done via a 50 mm HDPE main irrigation line into a 25 l/hr. dripper to achieve a flow rate of 12.5 l/hr. per planting tower.
5. Water is then allowed to flow via a 63 mm drainage pipe through another mechanical filter and is then collected back at the catchment tank and the process is restarted. The drain pipe is angled at less than 1% to allow gravitational flow into catchment tank.

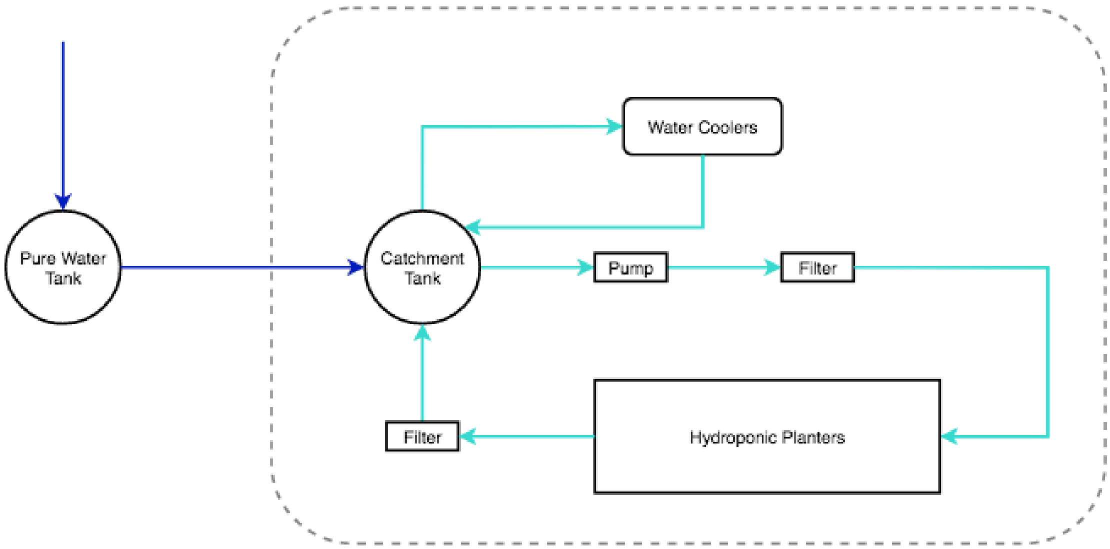

Figure 4.8: Design Setup.

A tower is a vertical composition of 8 planters assembled back-to-back (Figure 4.9). Each tower is 1,9 m high and 0.4 m in width. The space between them is 0.3 m. There are 6 rows in the tunnel each with 86 towers and a total of 1376 planters. There is a 1 m walkway between the rows (Figure 4.10).

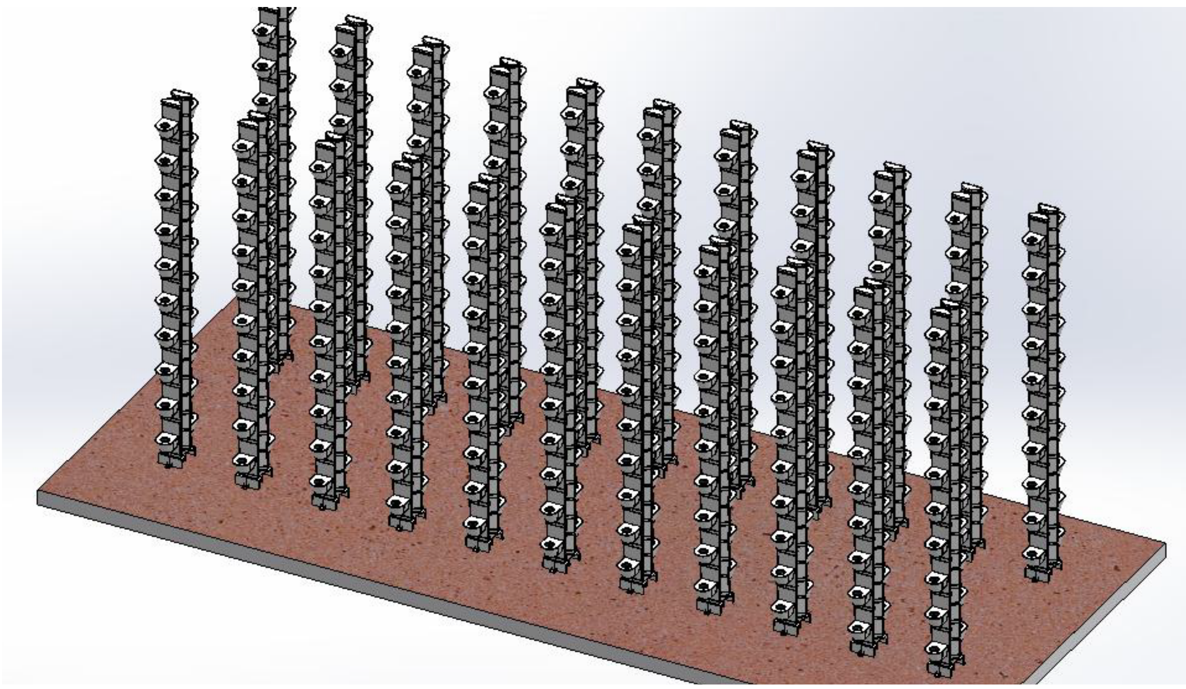

Figure 4.9: Planter Layout: the irrigation system was placed in an area of 10x3 m within the tunnel, while the planters occupy a space of 10x26. The water tanks were placed underground with the rest of the irrigation system above ground.

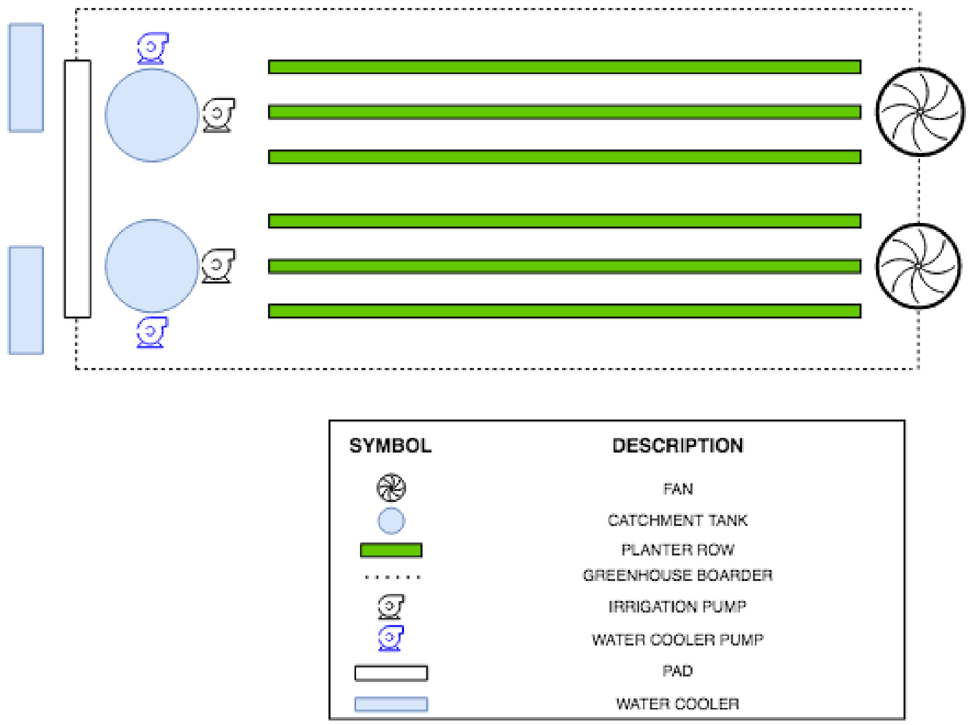

Figure 4.10: AB Farms tunnel design.

4.2.4 Research trial layout, statistical design, and treatments

Seedlings were acquired from an external supplier and planted according to the program shown in Table 4.1.

Two research treatments were tested Green and Red Oak Leaf lettuce. Each planting row consisted of four Green Oaks and four Red Oaks placed on top of each other and the rows were alternating between Green on top and Red on top. 1800 Green Oaks were planted and 1800 Red Oaks were planted for a total of 3600 plants. Currently the tunnel has a capacity of 7200 plants and can be configured to a maximum of 10 000 plants per cycle.

Table 4.1: Planting program.

Type	Crop	Time to Harvest	Plants per cycle
Lettuce	Green Oak Leaf	4-5 weeks	1 800 (25% of the structure)
	Red Oak Leaf		1 800 (25% of the structure)

4.2.5 Environmental monitoring

Air temperature was the only environmental variable monitored during the trial period, however the team aims at monitoring relative humidity, dew point and the amount of radiation penetrating through the structure.

4.2.6 Monitoring of nutrient solution and pH

A combination of fertilizers (Hygrotech's hygroponic mix and Omnia's Calcium Nitrate) and foliar feeding (Nitrosol) applications was performed (Table 4.2) in order to accomplish the target EC and pH values (Table 4.3). Pesticides were added on a preventative basis to make sure the crops are not infested with pests and diseases.

Table 4.2: Fertilizer application.

Element	Hygroponic mix	Nitrosol	Calcium Nitrate
Nitrogen(N)	68 g/kg	-	15.5%
Phosphate (P)	42 g/kg	-	-
Potassium (K)	208 g/kg	-	-
Magnesium (Mg)	30 g/kg	7 g/kg	-
Sulphur (S)	64 g/kg	4 g/kg	-
Iron (Fe)	1258 mg/kg	60 mg/kg	-
Manganese (Mn)	299 mg/kg	40 mg/kg	-
Zinc (Zn)	149 mg/kg	1 mg/kg	-
Copper (Cu)	22 mg/kg	1 mg/kg	-
Boron (B)	373 mg/kg	23 mg/kg	-
Molybdenum (Mo)	37 mg/kg	15 mg/kg	-
Calcium (Ca)	-	6 mg/kg	19.6%

In addition, the following practices were maintained on a regular basis to avoid the proliferation/incidence of pests and diseases:

1) Preventative cultural practices (cleanliness).
2) Monitoring of pests and diseases (scouting).

Table 4.3: Growth Parameters.

Type	**Crop**	**Target EC**	**Target pH**	**Target water temperature**	**Target air Temperature**
Lettuce	Green Oak Leaf Red Oak Leaf	2.2-2.6	6.2-6.8	18-28	18-28

Table 4.4 illustrates the variables to be monitored during the growth program of each planting cycle.

Table 4.4: Monitoring Details.

Variable	**Details**	**Frequency**	**Measurement tool**
Nutrient Solution	EC	3 times a day	HM Digital EC/TDS/Temp Meter COM100
	pH		HM pH Meter 80
	Temperature		HM Digital EC/TDS/Temp Meter COM100
Internal Temperature	Temperature	3 times a day	Muntas temperature sensor
Electricity usage	Total energy consumption	weekly	calculated
Water Usage	Input water – Drainage water	weekly	calculated
Average Mass of Plant	Kilograms	weekly	Clicks Kitchen Scale
Marketable yield	Number of saleable crops	Once per harvest	calculated

4.2.7 Water flow rates

Water flow rates were kept constant at 25 l/hr using pressure compensated drippers.

4.3 Results and discussion

4.3.1 Environmental variability

Notes as illustrated in Figures 4.11 to 4.14:

All temperature units are in Degrees Celsius (°C)

All Electrical Conductivity (EC) units are in miliSiemens per centimetre (mS/cm)

All seedlings were transplanted on the 7th of December 2021 and harvested on the 4-7th January 2022. Crops were grown over a 4 week period.

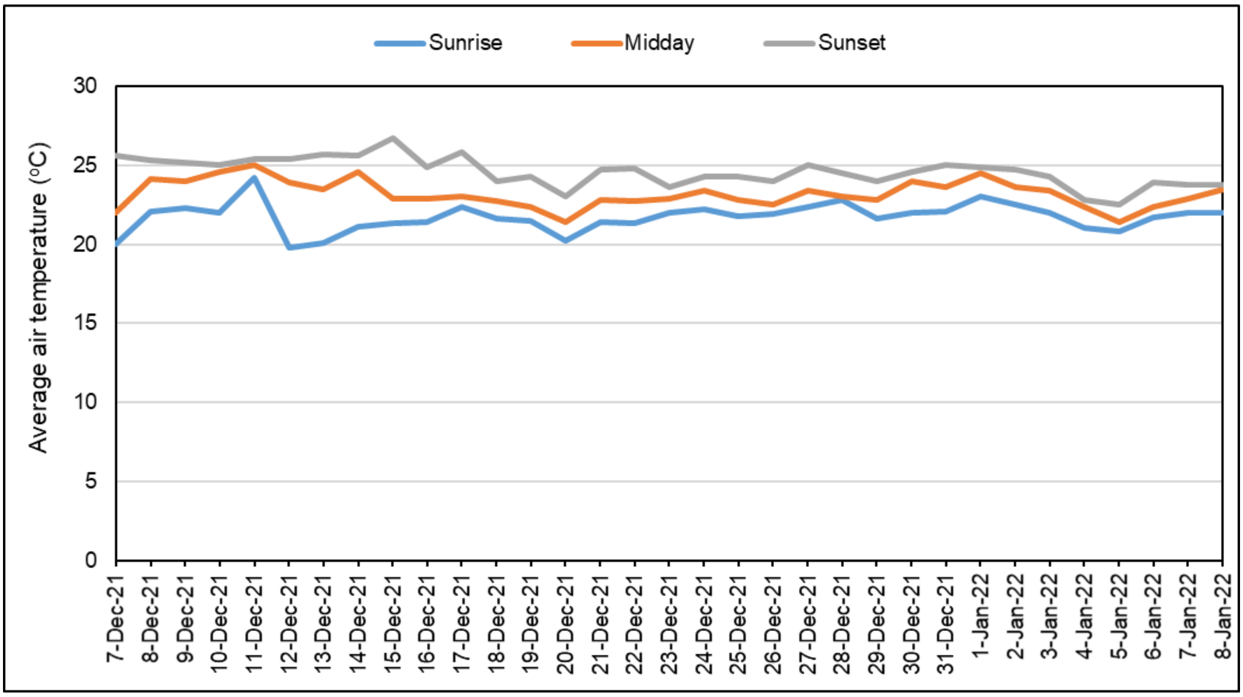

Figure 4.11: Average air temperature fluctuation inside the plastic tunnel at three different periods of the day.

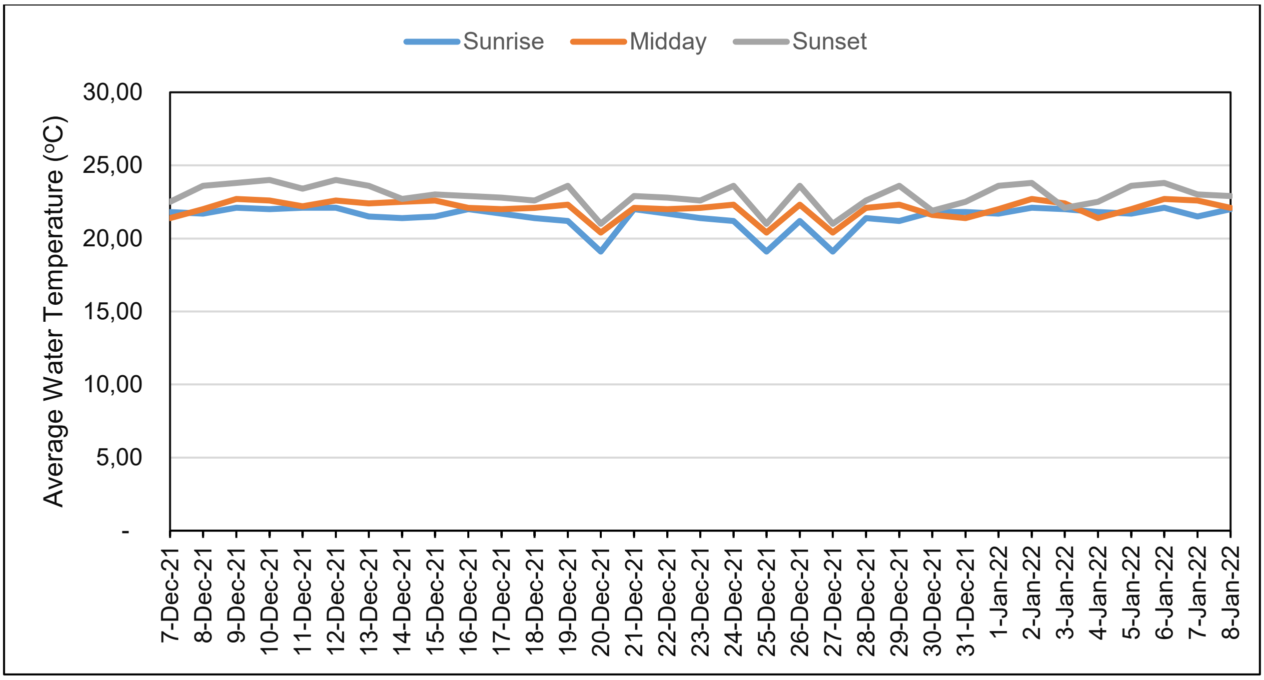

Figure 4.12: Average water temperature fluctuation inside the plastic tunnel at three different periods of the day.

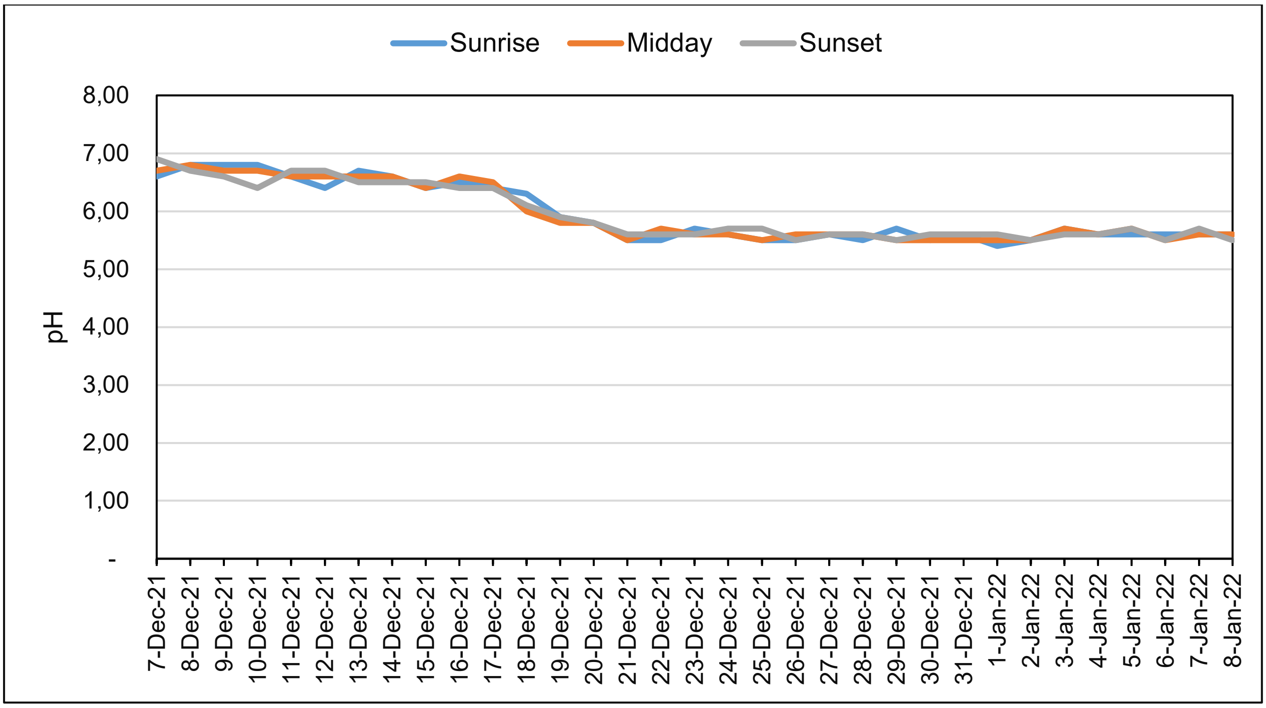

Figure 4.13: Nutrient solution pH fluctuation inside the plastic tunnel at three different periods of the day.

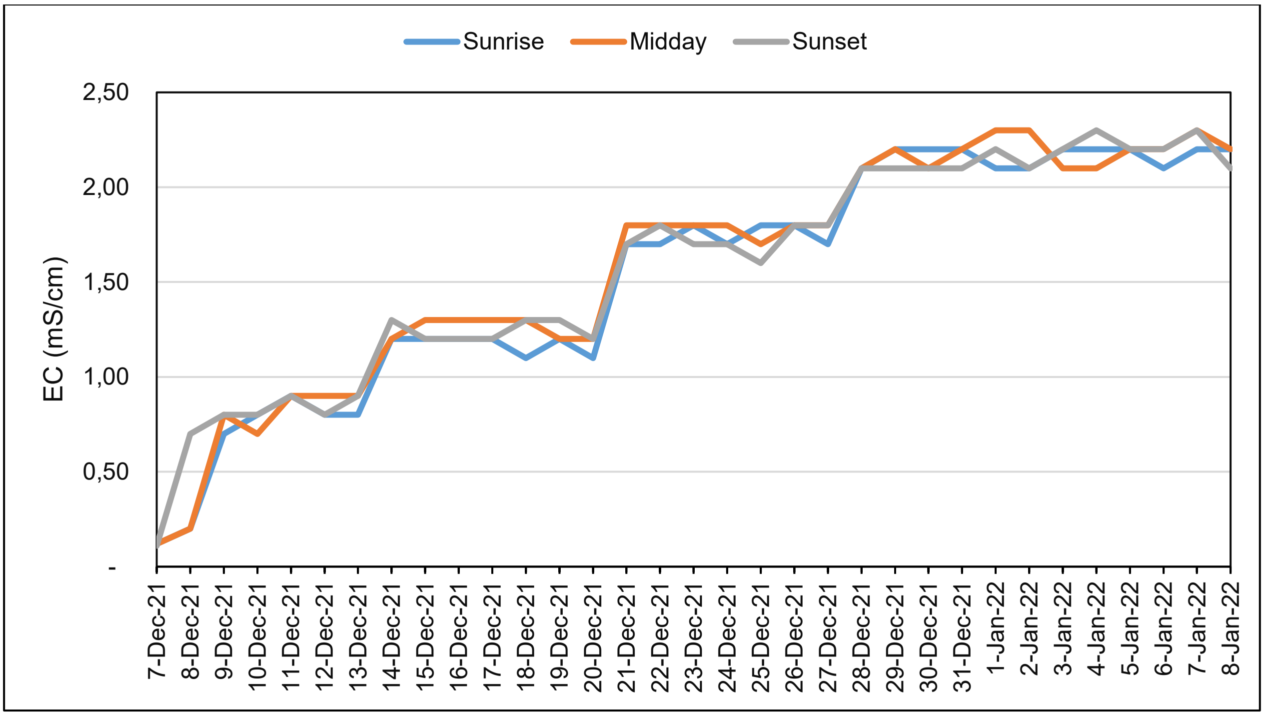

Figure 4.14: Fluctuation of electrical conductivity of the nutrient solution inside the plastic tunnel at three different periods of the day.

4.3.2 Water utilization

Crop water use will be measured during the next production cycle.

4.3.3 Plant physiological and pathological disorders

We had issues with white flies and aphids. Foliar feeding program (Table 4.5 and Figure 4.15).

Table 4.5: Pest incidence and control

	Week 1	Week 2	Week 3	Week 4
Multipurpose Aphids	5 ml / 20 l	-	5 ml/10 l	-

4.3.4 Plant growth

3600 heads of lettuce (1800 Green Oak and 1800 Red Oak) were planted in the system on the 7th December 2021 and Harvested between 4-7 January 2022. 10 Green Oak and 10 Red Oak plants were randomly selected and weighed throughout the growing cycle and the results are listed below. It is worth noting that the Green Oak seedlings came into the system noticeably smaller than the Red Oaks however they performed relatively comparatively well (Table 4.6). This is due to supplier inconsistency.

Table 4.6: Lettuce plant weight fluctuation.

Green Oak	**Week 1[g]**	**Week 2[g]**	**Week 3[g]**	**Week 4[g]**
Plant 1	37	69	110	178
Plant 2	36	72	105	173
Plant 3	33	65	107	178
Plant 4	35	71	102	177
Plant 5	40	72	108	181
Plant 6	40	71	102	173
Plant 7	35	67	103	175
Plant 8	38	70	106	182
Plant 9	38	67	105	179
Plant 10	32	68	105	178
Average[g]	**36,4**	**69,2**	**105,3**	**177,4**
Green Red Oak	**Week 1[g]**	**Week 2[g]**	**Week 3[g]**	**Week 4[g]**
Plant 1	47	91	117	186
Plant 2	43	88	105	183
Plant 3	44	85	113	187
Plant 4	45	83	102	184
Plant 5	46	83	119	185
Plant 6	45	90	112	184
Plant 7	43	84	111	179
Plant 8	44	85	114	181
Plant 9	45	90	107	182
Plant 10	44	92	109	180
Average [g]	**44,6**	**87,1**	**110,9**	**183,1**
Total Average [g]	**40,5**	**78,15**	**108,1**	**180,25**

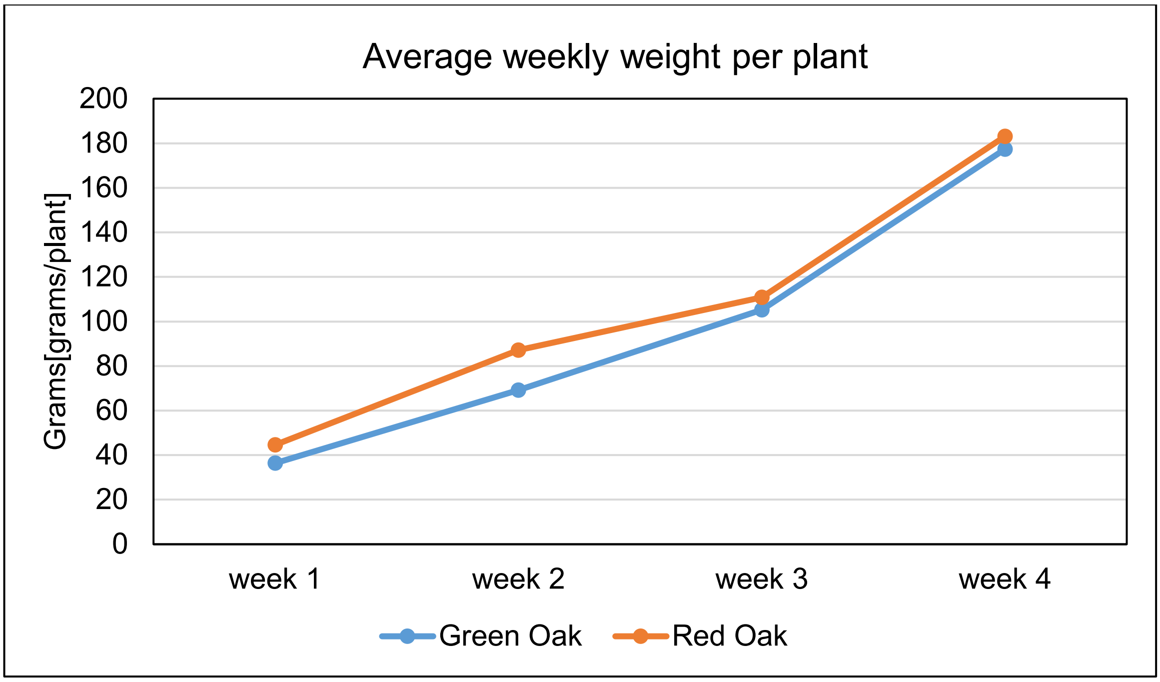

Figure 4.15: Lettuce plant average weight chart.

Below are pictures illustrating the lettuce production cycle (Figures 4.16 to 4.24).

Figure 4.16: Day of Planting.

Figure 4.17: 1st Week.

Figure 4.18: Day1 Green Oak Close-up.

Figure 4.19: Week 2.

Figure 4.20: Week 2 close-up.

Figure 4.21: Week 2 Green Oak Close-up.

Figure 4.22: Week 2-3.

Figure 4.23: Week 2-3 Close-up Red Oak.

Figure 4.24: Week 2-3 Close-up Green Oak.

4.3.5 Marketable and unmarketable crop yield

The shrinkage was 2.5% for the production cycle and the amount of marketable yield was 95% this is in line with our expectations. The average head weight was higher than expected, the average head weight is usually 120-160 g (Table 4.7). This is a positive as it illustrates that we could harvest some crops earlier than usual and hence fitting in more production cycles in a season.

Table 4.7: Production Outputs.

Outputs	Quantity	Percentage [%]
Amount of planted lettuce	3600	100
Amount of harvested lettuce	3510 (631.8 kg total kg)	97.5
Shrinkage(heads)	90	2.5
Marketable heads of lettuce	3420 (615.6 kg total kg)	95
Average head weight	180 g	-

4.4 Conclusions and recommendations

The production cycle was a success, and the system performed well as expected. The hydroponic planter operates as it was designed to operate. All the marketable heads were sold to VT Harvest an e VT Harvest, a Mogale City-based agribusiness that produces and packages herbs such as fennel, coriander, wild rocket, tomatoes, lettuce and spring onions. We packed the lettuce in 3 kg plastics and VT collected a total of 631.8 kg's with a refrigerated truck.

The research team experienced delays with the construction of our tunnel that will be used to carry out the next deliverable detailed below. The delays were due to a shortage of steel due to the NUMSA strike from 5 October 2021 to 21 October 2021. Although the strike was only 3 weeks long, it caused a backlog of orders and as a relatively small client we received our material 8 weeks late.

The team also encountered difficulties with one of the pumps just before the festive season and have sent it back to the manufacture for replacement under warranty.
As this is a new system there will always be teething problems which we address as and when they come up. Further testing is required to demonstrate consistency and to determine how much water and electricity the system requires when it is fully operational through the different seasons and with different crops.

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CHAPTER 5: ON-STATION DESIGN, SET-UP, OPERATION, TESTING AND EVALUATION OF THE GRAVEL AND NUTRIENT FILM RECIRCULATING HYDROPONIC SYSTEMS

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5.1 Introduction and background

Hydroponics, a soilless cultivation method, is eligible for crop production on arable and non-arable land (Choi et al., 2013). Now, with chances of acquiring land getting slimmer in most parts of the world, the idea of hydroponics is becoming more appealing to growers. The gravel film technique (GFT) has been well received and utilized worldwide and in South Africa for decades now (Maboko and Du Plooy, 2013; Thomaier et al., 2015). It is known for its excellent quality and quantity of produce, as well as uniform growth improvement. This is due to its even watering and fertilization patterns. Economically and nutritious crops such as sweet basil (*Ocimum basilicum*) are reported to be gaining popularity in recirculating hydroponics. This is because it possesses attractive variables such as flavour and appealing appearance. Sweet basil is a culinary and medicinal herb, with wide range of uses in the society, including essential oil production and ornamentals as a flower. However, it is mostly used as herb, because it contains important health beneficial phytochemicals that include antioxidants such as lutein, zeaxanthin, beta-carotene, and beta-cryptoxanthin. It is also a good source of several minerals, particularly micro-nutritional such as Vitamin A, Fe, Mn and Zn, which are reported to improve human immune system (Vlado et al., 2015). Many of basil's health benefits come from these antioxidants and micro-nutritional elements (Yang et al., 2020). For instance, antioxidants are responsible to fight free radicals which are unstable molecules that lead to cell damage and increased chances of various health complications such as cancer, arthritis, sugar diabetes, etc. (Yang et al., 2020). Similarly, micronutrients such as ion and zinc are deficiency in human being is the initial phase of malnutrition. As a result, health practitioners often recommend frequent consumption of this crop to prevent deadly ailments. Therefore, commercially it has been reported to be highly profitable herb (Souza et al., 2019). Hence, there is sudden demand for basil production increases commercially (Souza et al., 2019; Choi et al., 2013). With hydroponics being consistently reported as a reputable high quality production system for various crops commercially, the idea of producing high quality crops coupled with good quantity over small areas continues to attract people into farming. This is due to ability to achieve high profit even in water scarce and non-arable spaces (Souza et al., 2019; Muller et al., 2017). This is particularly true for urban areas where water scarcity is a limiting factor due to high population and intensive industrialization. However, in spite water scarcity, the inception of hydroponics in highly industrialised spaces has offered a great opportunity that ensure income generation for farmers in such highly competitive areas (Souza et al., 2019).

Water flow rate in the context of recirculating hydroponics systems is defined as the amount of water that can drip down the cropped area per unit time. It is an important factor that affects plant growth in soilless culture, as it determines the contact period of water and plants roots and ultimate nutrients uptake (Yang et al., 2020). Generally, recirculating hydroponic systems including the GFT use continuous water flow. But in some instances, like in ebb-and-flow hydroponic systems, intermittent water flow cycles can be used. The water flow rate is largely influenced by growing condition such as temperature and growth media (Al-Tawaha et al., 2018). For instance, increased temperatures increase the water evaporation and, while growing media determines the water holding capacity which alters the flow of water. Al-Tawaha et al. (2018) investigated three water flow rates (10, 20 and 30 L/h) on lettuce planted on peat moss growing medium, in a temperature regulated greenhouse that ranged from 16-22ºC. The results demonstrated that best lettuce production was obtained under the 20 L/h flow rate. These suggested that the water flow rate in the latter growing conditions could be lower compared to other growing conditions such as in the outdoor or shade nets. For instance, Chiloane (2012) conducted a study to determine optimal electrical conductivity (EC) concentrations for lettuce on constant flow rate of 18 L/h during winter with temperature range from 5 to 20ºC. Similarly, Maboko et al. (2013) studied different plant densities on basil on constant flow rate of 42 L/h and the temperature ranged from 23 to 30ºC.

However, it is important to mention that both the latter studies were conducted in a shade net and gravel as the growing medium. The observation on these studies confirms the suggestion that flow rate depends on the type of growing media temperature of the growing conditions. Because, the lettuce trial was done in cool season (winter) which had low flow rate (18 L/h) (Maboko and Du Plooy, 2009) whereas basil study was done during hot season (summer) hence it had high flow rate (42 L/h) (Maboko and Du Plooy, 2013). Gravel can easily be affected by temperature, for instance it gets very hot in high temperature areas, which will increase the evaporation rate. Furthermore, the length of the gullies determines the time water flows in the gravel, which influences evaporation. Hence, it is important to determine the appropriate water flow rate in recirculating hydroponic systems.

Another challenging aspect in recirculating hydroponic systems is the management of fertilizers to maximize growth and yield. Fertilizers are expensive inputs that need high level of efficiency, and as a result, EC (a measure of total soluble salts) is incorporated as an important aspect of hydroponics to maximise crop yields. For instance, excessively high levels of EC can induce salinity stress, ion toxicity and nutrient imbalance more prevalent in a closed hydroponic system, whereas excessively low EC values are mostly accompanied by nutrient deficiencies and reduction of plant growth (Rosa-Rodríguez et al., 2020). However, determination of optimal EC concentrations is dependent on crop type and growth stage. Generally, crops nutrients consumption increases with crop growth until optimal EC level. Some leafy crops such as Kale and mustard are heavy feeders, whereas crops such as lettuce and watercress are light feeders (Parks et al., 2009). However, crops such as baby spinach grow well in high EC that is up to 2.9 mScm and normal leafy crops EC 1.6 to 2.4 mScm (Vandam et al., 2017). Vigorous growth and shortened life span is experienced in high EC (Vandam et al., 2017). This implies that salt sensitivity and biomass accumulation is crop dependent. Therefore, EC thresholds should be adjusted and maintained within the optimal EC range. This is equally important as maintaining an adequate water flow rate, which are often overlooked crucial aspects in hydroponic production systems. If these aspects are taken into consideration, growers can be in better position to measure and manipulate water use efficiency and nutritional water productivity in the recirculating hydroponics systems. To date, there is little information on optimal EC and flow rates in active recovery hydroponic system. Therefore, the present study aims to identify an optimal EC level and water flow rate for basil grown in GFT under a shade net structure.

Vertical farming is another hydroponics method that has been studied lately to explore ways to improve crop productivity under efficient methods (Despommier, 2010; Sihlongonyane, 2020). This is after the realisation that important resources such as water, land and fertilizers are becoming more limited (Despommier, 2010). Hydroponics was introduced as a tool save water and space mostly. However, recently these important resources are becoming more scarce while food production is expected to increase exponentially. This is due to the inevitable human population increase and migration to urban areas. The available land in urban areas is more contested due to various businesses operating in the same space. This makes the space expensive, which warrants efficient utilization of the available resources. The adaptation of hydroponics into vertical farming was due to various motives. Despite saving water and space, the motives for hydroponics include reduced transportation costs to retail stores and restaurants, delivery of better quality and freshness and production of food in environmentally friendly spaces. The breakthrough on the use of light emitting diode (LED) and Controlled

Environment Agriculture (CEA) to influence the photosynthetic process of plants increased the adoption of vertical farming systems (Thomaier et al., 2015). This allowed the introduction of plant factories in the heart of urban areas. Old building structures were repurposed for food productions. Lettuce is one of the most important leafy vegetables that is produced in hydroponic systems, particularly in vertical farming (Mohammed et al., 2016). It is a highly nutritious crop, rich in important vitamins such as vitamin A, C, E, K), polyphenols, and antioxidant compounds. Due to its short size and production cycle, lettuce is a model plant for vertical farming studies and attracts a high interest for commercial production in vertical farming systems (Mohammed et al., 2016).

Despite rich information of lettuce cultivation under recirculating hydroponic systems, either in vertical farming or horizontal systems, information on water supply interactions with planting densities remains undocumented (WIBC, 2019). These are some of the important agronomic aspects that may be used to enhance resource efficiencies in vertical recirculating hydroponic systems. For instance, in recirculating systems the water can be supplied through intermittent or continuous flow. The intermittent water flow pattern has the potential to save water and energy greatly (Adzman et al., 2021). Plant spacing is another important factor that if not properly managed may affect the growth and yield of crops tremendously (Maboko and Du Plooy, 2009). Maboko and Du Plooy (2009) indicated that lettuce leaf area is greatly affected by planting spacing. The findings indicated that dense population increase yield of lettuce when compared to widely spaced lettuce. Souzer et al. (2019) further, indicated that leaf area of the leafy lettuce affects market supply. For instance, large leaf area may be harvested and sold multiple times to restaurants, whereas small area lettuce may be harvested as head once off only, for supermarkets.

Water as a resource is important in everyday life and particularly for production of food. Production of food has since been sustained by irrigation as the main supply of water. This has since challenged sustainability of fresh water supply globally and South Africa as one of the water scarce countries. Strategies to increase precision in water use for agriculture has been proposed including recirculating hydroponics systems (Sihlongonyane, 2020). In these systems, water supply consists of two methods namely continuous and intermittent recirculating water supply. Continuous supply means recirculating of water 24/7 without pausing, the plant roots are always suspended into a net film of water passing through the PVC pipe, it is normally practiced when plant roots have no organic growth media (Grewal et al., 2011). This helps plants to be able to respond the environment and match the vapour pressure deficit demand. the biggest advantage of this method is that it reduces the amount of dirt (growth media) during production. Cardoso (2018), also indicated that the system is most suited for crops like living lettuce that is harvested with roots. Contrary to that, the disadvantage of this method is that production may be lost should there be power failure for a short period of time. On the other hand, the intermittent water supply pattern refers to timed watering cycles a daily basis. This method's main advantage is the ability to save energy and water when compared to continuous water supply (Adzman et al., 2021). The production may be able to survive without water for several hours depending on the growth media used or the growth pipe design. However, the choice of these methods heavily depends on the environmental structures that are used. This is because the environmental condition is the central driver of vapour pressure deficit (Michelon et al., 2020).

Environmental conditions are an important aspect of all agricultural operations and hydroponics is no exception. Environmental conditions such as sunlight, temperature, relative humidity and air circulation play major parts of crop growth. The idea of hydroponics was to control major and essential factors of crop growth (Despommier, 2010). This was to better manage the risks associated with uncontrollable and unpredictable environmental conditions (Thomaier et al., 2015). Therefore, hydroponics is usually cultivated indoors of structural constructions such as rooftops, tunnels, shade nets and buildings. Now, to control these environmental conditions, the modern idea of hydroponics uses the concept of CEA (Thomaier et al., 2015). The CEA concept employs high technology to create an ideal environment for plant growth. The concept optimizes environmental conditions (humidity, temperature, gases and light) for maximum crop growth and productivity (Chang *et al*., 2005). However, the start-up and maintenance cost for CEA are very high and unattainable for local emerging farmers, South Africans in particular (WIBC, 2019). Nevertheless, hydroponic farms are very diverse, both structurally and technologically. For instance, some rely on natural ventilation methods where tunnel and shade net are often considered. Resource-poor growers are producing under shade nets and in high tunnels that are not temperature-controlled because of the large capital investment required for controlled infrastructures (WIBC, 2019; Pulela et al., 2020). In this regard, it is very important to consider the positioning of the hydroponic structure to ensure sufficient sunlight and ventilation (Pulela et al., 2020). Although leafy vegetable crops can partially tolerate shade, fruiting crops need sufficient light for the production of optimal fruit. The principle behind the active recovery hydroponic systems is to recirculate water and nutrients to ensure efficient use of these resources (Guo et al., 2019). Generally, plants are grown in shade net or plastic tunnel to protect them against the strong UV radiation, to increase the humidity around plants, and to decrease to some extent the extreme minimum and maximum temperatures that can occur in one single day. Naturally, ventilated high-tunnel, protected culture is suitable for off-season cultivation of *Cucumis melo* (Sugani and Varma, 2014). High, and low, plastic tunnels have been an important tool for crop production on and off the season extension enabling growers to create a microclimate better suited to warm-season crops such as basil, tomatoes, melons, etc. (Lamont, 1996). Plastic tunnel is made of polyethylene, usually semi-circular, square or elongated in shape. Plastic tunnels are generally preferred in temperate regions because the interior heats up because incoming solar radiation from the sun warms plants, and other things inside the tunnel faster than heat can escape the structure (Sugani and Varma, 2014). Therefore, manual opening and closing of tunnel flaps is common practice to control temperature, humidity and aeriation. Shade net covers and protect crops from direct sunrays and reduces the ambient temperature around plants. It is usually used in hot climates around the world, vegetables are grown under shade net to reduce heat and light intensity, resulting in better quality and higher yields (Maboko and Du Plooy, 2013). Shade net is a weather-resistant woven or knitted fabric that is available in densities ranging from 12 to 90 percent (Sugani and Varma, 2014). The density represents the percentage of light that penetrates through the cloth; for example, a 47 percent shade cloth allows 47 percent of light penetration. Most vegetables should be grown under 30 to 50 percent shade (Chang et al., 2005). Growing conditions are important for some of the hydroponic sources of attraction such as marketable yield and quality. For instance, protection against harsh environmental conditions such as strong winds help to preserve crop quality. This is one of the attractants of the hydroponics cultivation, which is the ability to produce high quality commodity (Souza et al., 2019).

Plant spacing is the space defined between plants and rows, and it is used to get the overall plant population per unit cultivated area. It has been an important aspect in agriculture because it is used to optimise crop yield and quality (Maboko et al., 2009). Understanding the crop's response to plant density is vital for growers to maximize crop yield. For instance, Maboko and Du Plooy (2009) reported that planting too high or too low numbers of plants per unit area could result in lower yields and quality, as compared to optimum planting densities. In the context of soil-based agriculture, the principle is that, too high planting densities could result in increased competition for water, solar radiation and nutrients. This ultimately results in poor biomass accumulation and eventually poor yields and quality of produce. In contrast, using too low planting densities could result in low yields per total cultivated area. Therefore, optimal planting densities should be determined for specific crops. However, in hydroponics, it is widely reported that increased planting densities increases crop yield due to a non-limited supply of water and nutrients to the crops. For instance, Maboko and Du Plooy (2009) studied the optimal planting density for lettuce in a GFT system. The results demonstrated that major plant growth variables, such as plant height, leaf area and leaf number, increased with an increase in plant density. The narrowed spacing, which was 50 and 40 plants/m^2, produced taller plants, with an average height of 197.1 mm and 192.1 mm, respectively, when compared to the widely spaced plant densities of 20 and 25 plants/m^2 that resulted in shorter plants with heights of 14.7 and 15.9 cm, respectively. Many authors reported that this is attributed to increased competition for solar radiation and more energy being channelled for vegetative growth (Maboko et al., 2011; Cardoso et al., 2018). The present study, aimed at investing the interaction effects of water supply and planting densities on leafy lettuce grown in a vertical recirculating hydroponic systems under two different environmental conditions.

5.1.1 Problem statement

Active recirculating hydroponics systems are gaining worldwide popularity due to its ability to cultivate in no arable land (Agrizzi, 2017). Small scale farmers are keen to venture into this production systems (Sihlongonyane, 2020). However, important resources such as water and fertilizers are getting scarce and unaffordable (WIBC, 2019). Therefore, agronomic practices that increases precision and efficiency of inputs need to be introduced (Sihlongonyane, 2020). The present study was carried out to determine the optimal water use efficiency and nutrients level in production of sweet basil.

Cultivation of leafy vegetables in recirculating hydroponic systems has been reported to produce vigorous growth and higher yields per unit area (Niederwieser and Du Plooy, 2014). The introduction of vertical farming systems has increased hydroponic advantage by using less space for cultivations (WIBC, 2019). Smallholder farmers are looking to venture into these highly efficient agricultural developments (WIBC, 2019; Sihlongonyane, 2020). However, important resources such as water are getting scarcer, and more efficient methods need to be developed. For instance, water consumption under different planting densities has not been documented. Therefore, the present study aimed to determine the interaction between planting densities and water flow patterns on crop water USE and water use efficiency under different environmental conditions.

5.1.2 Study aim and objectives

- The aim of the study is to improve water and fertilizer resources management and planning in gravel and nutrient film recirculating hydroponic systems.

The objectives are as follows:

- To determine optimal nutrient concentration for vigorous growth and yield of herbs (using sweet basil as an example);
- To assess water use and water use efficiency of the Sweet basil grown in a GFT system under varying EC levels and water flow rates.
- To determine the optimal planting density for lettuce grown in vertical nutrient film technique in two different growing conditions
- To quantify the water use and determine water use efficiency of leafy lettuce grown in a vertical nutrient film technique.

5.2 Research methodology

Experiments was conducted at the Agricultural Research Council – Vegetable, industrial and Medicinal Plants (ARC-VIMP), located in Roodeplaat, South of Pretoria, South Africa (25°59' S; 28°35' E) during the winter period of 2021 (from October 2020 to February 2021).

5.2.1 Hydroponic structure and System design characteristics

The gravel film technique (GFT) was implemented under a 60% white shade net. Eighteen gravel beds made of black troughs were supported by the reinforce steel. The black troughs of size 139 cm x 76 cm x 11 cm were placed at a slope of 3% which allowed a water speed of 0.0537 m/s. Black plastic drums (100 L in volume) were placed under the gravel beds to be used as nutrient solution reservoirs for the supply and recover of the recirculating solution (Figure 65).

Figure 5.1: Black trough supported by stainless steel and drums below.

A small submersible pond water pump of 600 L/h maximum water flow rate (Grech Submersible Fountain Water Pump, Grech HJ-542, Pretoria) was immersed in each drum to pump the nutrient-filled water solution to the plant roots (Figure 5.2). The solution was redirected back to the drum through gravitation.

Figure 5.2: A small submersible pond water pump (Grech Submersible Fountain Water Pump, Grech HJ-542, Pretoria) with 600 L/h maximum water flow rate.

Soilless culture experiments were conducted at the Agricultural Research Council – Vegetable, industrial and Medicinal Plants (ARC-VIMP), located in Roodeplaat, South of Pretoria, South Africa (25°59' S; 28°35' E). The experiments were conducted in different environmental conditions (non-temperature-controlled plastic tunnel and a 60% white shade net structure were used as the growing conditions). The system design consists of a nutrient film technique (NFT) hydroponic system, where polyvinyl chloride (PVC) pipes, steel support, 25 mm pipes and drip spaghetti tubes are used. The operation is through recirculation of a nutrient enriched solution. An A-frame structure was made of steel frame, PVC pipes (including manifold and drain pipes), PVC pipe caps, irrigation pipes and couplings, electrical connection and net cups (diameter = 50 mm; depth = 54 mm). The steel structure was designed with a length, base and height of 2, 1.8, and 2 m, respectively. The production area was 2 × 0.48 m^2 per single PVC pipe. The 0.95 m^2 PVC pipes were stacked on the frame and connected to one water tank of 200 L. Holes of 50 mm in diameter were drilled along he pipes to accommodate the growing net cups. Seedlings were planted in net cups containing cocopeat as the growing media. A submersible electric pump was inserted into each of the 200 L tanks. The solution was pumped from the reservoir to a 25 mm pipe manifold that was connected to drip spaghetti tubes. Valves were installed in the 25 mm water circulation pipes to regulate the water flow rates. An average water flow rate of 10 L/min was maintained along the growing pipes. Each spaghetti tube released water into the PVC pipes that were slightly slopped to allow water flow into the recovering 20 mm pipe. The 20 mm pipe recovered the water and directed back into the reservoir. The plants in the net cups were suspended in PVC pipes where a 2-4 cm film of water was flowing downward. Plant roots expanded over time to take up nutrients and water from the shallow film of nutrient solution flowing through the growing pipe.

5.2.2 Research trial layout, statistical design and treatments

The trial was laid in a 2 × 3 factorial design arranged in a randomized complete block design (RCBD), with three replications. The factors were water flow rate (24 and 48 L/hr) and nutrient concentrations (1.0-1.5, 2.0-2.5 and 3.0-3.5 mS/cm). The flow rate of the nutrient solution was adjusted using a ball-valve to release 24 and 48 L/h according to the treatments. The pump ran for 24 hours a day, every other day. (Figure 5.3) illustrates the trial layout the treatments.

Block 1	
1-1.5 $mScm^{-1}$ × 24 L/h	2.0-2.0 $mScm^{-1}$ × 48 L/h
3.0-3.5 $mScm^{-1}$ × 48 L/h	3.0-3.5 $mScm^{-1}$ × 24 L/h
2.0-2.5 $mScm^{-1}$ × 24 L/h	1-1.5 $mScm^{-1}$ × 48 L/h

Block 2	
3.0-3.5 $mScm^{-1}$ × 48 L/h	2.0-2.5 $mScm^{-1}$ × 24 L/h
1-1.5 $mScm^{-1}$ × 24 L/h	1-1.5 $mScm^{-1}$ × 48 L/h
3.0-3.5 dSm^{-1} × 24 L/h	2.0-2.5 $mScm^{-1}$ × 48 L/h

Block 3	
1-1.5 $mScm^{-1}$ × 24 L/h	1-1.5 $mScm^{-1}$ × 48 L/h
3.0-3.5 $mScm^{-1}$ × 48 L/h	3.0-3.5 $mScm^{-1}$ × 24 L/h
2.0-2.5 $mScm^{-1}$ × 48 L/h	2.0-2.5 $mScm^{-1}$ × 24 L/h

Figure 5.3: Trial layout to investigate the influence of nutrient solution concentrations and water flow rates in a gravel film nutrient technique.

The lettuce experiment consisted of a 2 x 3 factorial arrangement laid out in a randomized complete block design. The factors were plant spacing (10, 20 and 30 cm between plants) and water flow patterns (continuous and intermittent water supply). Therefore, the trial consisted of six treatments which were replicated three times in two different types of hydroponic structure (non-temperature-controlled plastic tunnel and 60% white shade net). The trial layout is shown in (Figure 5.4).

Block 1		Block 2		Block 3	
10 cm × Con	20 cm × Inter	20 cm × Con	30 cm × Inter	30 cm × Con	20 cm × Inter
20 cm × Con	10 cm × Inter	10 cm × Con	20 cm × inter	20 cm × Con	10 cm × Inter
30 m × Con	30 cm × inter	30 cm × Con	10 cm × inter	10 cm × Con	30 cm × Inter

Figure 5.4: Lettuce trial layout set-up at ARC-VIMP. Con = Continuous water supply; Inter = intermittent water supply.

5.2.3 Environmental monitoring

Weather variables such temperature, humidity, wind speed, wind direction, rainfall and barometric pressure were measured using a 5-in-1 automatic weather station installed on-site (Davis Vantage Vue) (Figure 5.5). The data was recorded on an hourly basis.

Figure 5.5: Davies weather station data logger (a) and atmospheric sensors (b).

5.2.4 Monitoring of nutrient solution and pH

The pH and EC of the nutrient solution were measured and recorded on a daily basis using pH & EC combo meter (Hanna Instruments, Mauritius). Nutrients were applied through fertigation using water-soluble fertilizers (Hygroponic® (Hygrotech (Pty). Ltd., South Africa) and Calcium nitrate (Hygrotech (Pty). Ltd., South Africa). Hygroponic fertilizer comprised of the following mineral nutrient concentrations: comprising of N (68 mg/kg), P (42 mg/kg), K (208 mg/kg), Mg (30 mg/kg), S (64 mg/kg), Fe (1.254 mg/kg), Cu (0.022 mg/kg), Zn (0.149 mg/kg), Mn (0.299 mg/kg), B (0.373 mg/kg) and Mo (0.037 mg/kg), while calcium nitrate $[Ca(NO_3)^2]$ comprising of N (117 mg/kg) and Ca (166 mg/kg). (Figure 5.6) shows the hydroponic soluble fertilizers used, including the combo meter.

Figure 5.6: Hygroponic (a) and Calcium Nitrate (b) multi-component water soluble hydroponic fertilizers (c) Combo device (HANNA) used to measure Electrical conductivity in a solution. Adapted from (Araya and Moremi, 2021).

The system was monitored daily to ensure a balanced nutrient concentration (Maboko et al., 2012). Water was re-filled bi-weekly in absence of rainfall, while EC and pH while were readjusted manually to the specified ranges to avoid wastage. (Table 5.1) illustrates the amount of fertilizer applied to each treatment.

Table 5.1: Type and amount of fertilizer applied as treatments per 100 L of water.

	Concentrations after transplanting to one week		Concentration after one week	
Electrical conductivity level (mS/cm)	Hygroponic (g/100 L)	Calcium nitrate(g/100 L)	Hygroponic (g/100 L)	Calcium nitrate (g/100 L)
1.0-1.5	30	30	30	30
2.0-2.5	30	30	65	65
3.0-3.5	30	30	90	90

In addition, the EC level and temperature of the nutrient solution were measured automatically using an EM50 data logger every hour (Decagon Devices). This was done to assess the variability of EC levels during and post rainfall events since the trial was conducted under a shade net.

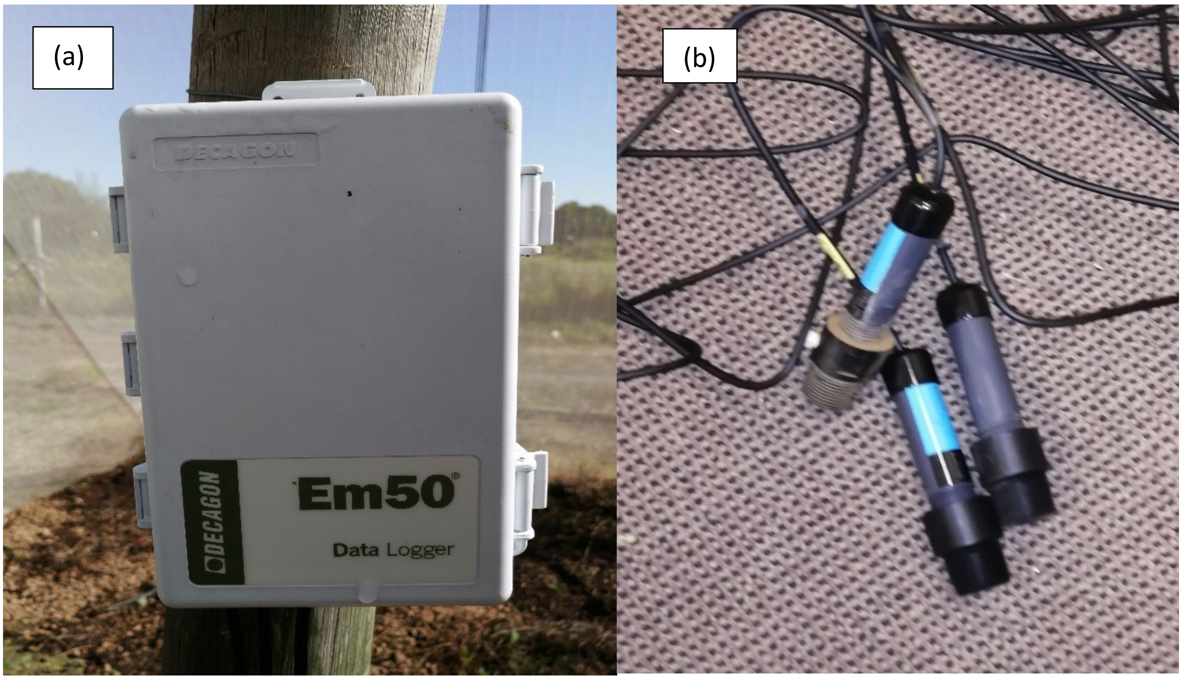

Figure 5.7: Decagon Em50 data logger (a); Electrical conductivity and temperature sensors (b).

5.2.5 Water flow rates

The flow rate of the nutrient solution was adjusted using a ball-valve to release 24 and 48 L/h according to the treatments. The pump was run continuously for 24 hours a day. Daily changes in water consumption (crop evapotranspiration) were monitored by measuring the water depth in the drum using a tape measure (Figure 5.8).

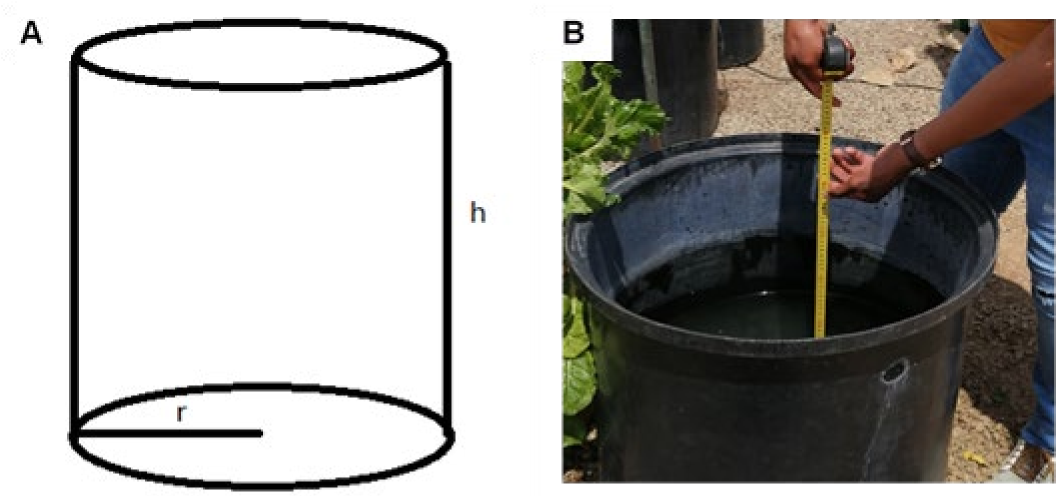

Figure 5.8: The sketch shows the variables that are used to measure water volume in conical shaped drum (a); Shows how the depth of the water will be measured with a tape (b).

Measurements were conducted every day, except weekends at 12 pm. The actual depth was used to calculate the total water in the drum, while the change in depth was taken as the amount of water consumed or evapotranspired by the plant. The volume of the water was calculated using a cylinder equation, as follows:

$V = r^2 \pi h$ Equation 1

where r = radius, π = 3.14 and h = height (depth of water in the drum). The amount of water used was divided by the total number of plants to obtain the water used per plant per day.

5.2.6 Data collection and statistical analysis

The following growth and physiological parameters were taken: (1) plant height using a tape measure; (2) leaf area index using ceptometer (ACCUPAR LP-80, METER GROUP USA); (3) leaf area using a light leaf area meter (LI-3100 area meter, USA and (4) leaf chlorophyll content using a Chlorophyll Meter (SPAD-502Plus, Europe). This data was captured every other harvest including fresh yield. Transplanting of seedlings was done on 11 November 2020. First harvest was taken at 30 days after transplanting (04 December 2020), second harvest after 21 December 2020, third harvest after 02 January 2021, fourth harvest after 27 January 2021 while the fifth after 17 February 2021. A sample of six plants was randomly selected in the middle of each experimental unit and labelled. Data for analysis was collected from the same sample at every harvest.

Crop water use efficiency (WUE) (kg m^{-3}) was determined according to Bos (1985) and Renault and Wallander (2000) using the equation below:

WUE = Y/ET Equation 2

Where Y is the total yield and ET is the actual evapotranspiration. The ET formula for hydroponics adapted from The ET was determined according to Ferreira dos Santos et al. (2019) using the formula below:

$$VETC = \frac{(Lf - Li) \times \pi \times D^2 \times 10^3}{4 \times n \times \Delta t}$$ Equation 3

Where VETC is the evapotranspirated volume of water, Lf is the final reading of the water level in the tank, Li is the initial reading of the water level in the filling tank, D is the internal diameter of the tank, ΔT is the time interval between readings, days; n is the population number of plants grown per plot.

The collected data was sent to ARC-biometrics department in Hatfield Pretoria for analysis. The data were analysed using analysis of variance (ANOVA) with the aid of statistical program

GenStat® version 11.1 (Payne et al., 2008). Significant means were separated using Fisher's protected t-test least significant difference (LSD) at the 5% level of significance.

5.3 Results and discussion

5.3.1 Sweet basil experiment under a gravel film technique

5.3.1.1 Crop water use under varying EC levels and water flow rates

The interaction between the EC and water flow rates had no significant effects on water use. However, the water flow rate had high significant effects on crop water use (Table 2). Similar findings as those presented in (Table 46), where interacting factors (different EC sources and water flow rates) did not affect crop water use of cauliflower, whereas water flow rates affected water consumption, were reported by Cruz et al. (2021). Water flow rate is defined as the amount of water that can drip down the cropped area per unit time (Al-Tawaha et al., 2018). It is an important factor that affects plant growth in soilless culture, as it determines the contact period of water and plants roots and ultimate nutrients uptake (Yang et al., 2020). The present study demonstrated that the sweet basil plant used an average of 11 and 20 L/season for 24 and 48 L/h flow rates respectively (8). This shows that less water was significantly used in the low water flow rate. Generally, low discharge of water per unit time increases water use efficiency. Furthermore, more water in the rhizosphere is more prevalent to evaporation. Cruz et al. (2021) also reported that cauliflower used on average 51.8 and 56.91 g L-1 for the flow rates of 1.5 and 2.5 L min-1, respectively.

Although the varying nutrient solution concentrations did not affect water use of sweet basil, the patterns indicate that the higher the concentrations the higher the water use. This outcome is generally not common in crops grown in recirculating hydroponics systems (Paulus et al., 2012; Cruz et al., 2021). According to Paulus et al. (2012), water consumption decreases in crops such as Lettuce and cauliflower when subjected to saline stress in the rhizosphere. This reported stress is due to the osmotic effect caused by the salts, which alter water uptake. Furthermore, decreased transpiration and water stress realised. The contradiction may be due to the sweet basil ability to strive under saline conditions. Sweet basil has been reported to be tolerant to salts up to 4 mS/cm and moderately tolerant to salts at 6 mS/cm (Ramin, 2006). Therefore, this suggest that water uptake and growth of sweet basil was not influenced by the saline concentration as the used levels were all below the stipulated saline levels for sweet basil.

Table 5.2: Analysis of variance for Water use affected by water flow rate, electrical conductivity and interactions in Gravel film technique system.

Source of variation	df	MS Water use (kg/L)
Rep	2	1.03
Flow rate	1	380.86***
EC	2	11.35ns
Flow rate .EC	2	1.74ns
Error	10	10.05
Total	17	

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%; df = Degrees of freedom, MS = Mean squares.

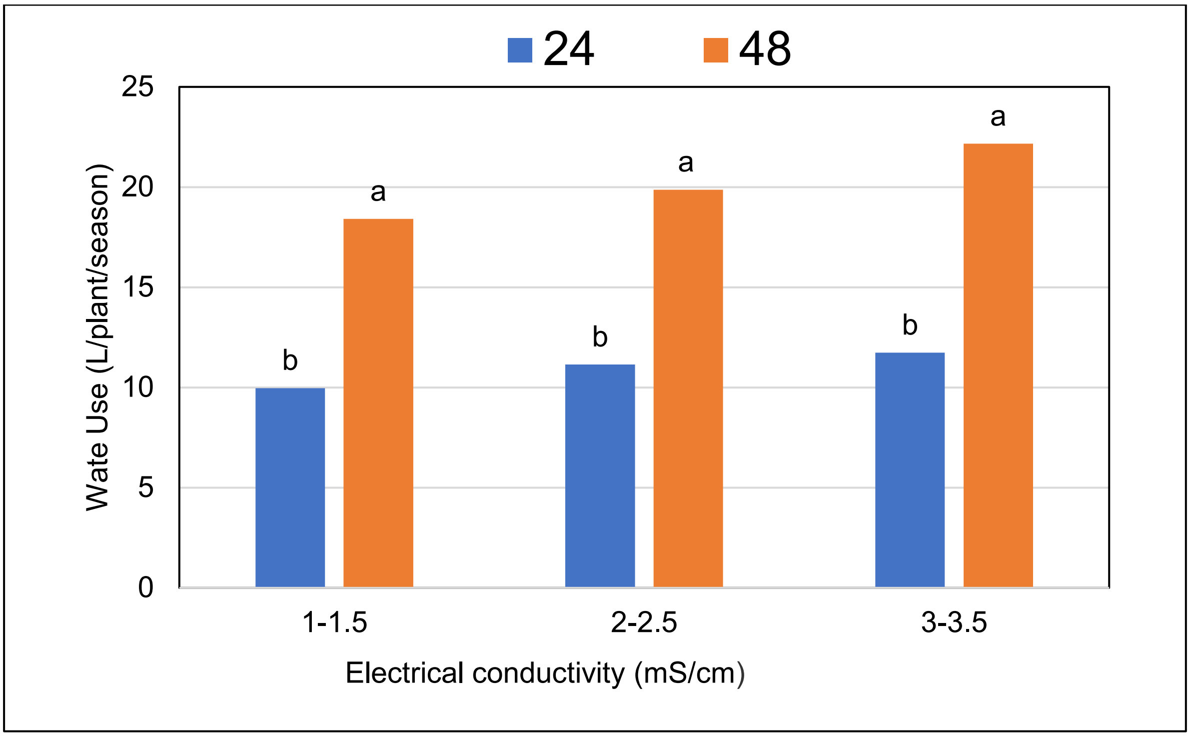

Figure 5.9: Seasonal water use of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity, water flow rate and the interaction.

5.3.1.2 Marketable and unmarketable yield

The total and marketable yield were significantly affected by the EC levels (Table 5.3). Total yield demonstrates that the highest output was realized at the highest concentrations (3.0-3.5). However, the highest marketable yield was achieved at the moderate EC concentration (2.0-2.5 mS/cm), as shown in (Figure 5.10). These two highest yields were both achieved at the flow rate 24 L/h interaction. This may be due various abiotic factors affecting the growing conditions. For instance, adequate supply of nutrients has been reported to stimulate plant growth. Sweet basil has been reported to be both moderate and heavy feeder when nutrients are in abundance (Baiyin et al., 2021). Hence, the highest total yield was observed at the highest EC concentrations. However, high EC concentrations have been reported to induce curly leaves which result in unmarketable fresh produce. Leaf biomass accumulation and expansion are the main indexes for measuring sweet basil yield (Baiyin et al., 2021). Therefore, leaf growth is heavily associated with accumulation of the nitrogen (Baiyin et al., 2021). Nitrogen when is supplied in abundance alters the salinity in form of $NaCl^-$ or r $CaCl_2^-$. Thus, according to Baiyin et al. (2021) this may induce nutrient imbalances for sweet basil and in some instances reduce calcium uptake. The lowest EC concentration (1.0-1.5 mS/cm) had the most unmarketable yield because of the visible deficiencies on the leaves for several micro and macro elements.

Table 5.3: Analysis of variance for total, marketable and unmarketable seasonal yield affected by water flow rate, electrical conductivity and interactions in Gravel film technique system.

Source of variation	df	MS		
		Total yield (kg/m^2)	Marketable yield (kg/m^2)	Unmarketable yield (kg/m^2)
Rep	2	0.0050	0.001176	0.0013139
Flow rate	1	4.0031^{ns}	0.002194^{ns}	0.0000380^{ns}
EC	2	12.9790***	0.022222***	0.0009730^{ns}
Flow rate .EC	2	0.0522^{ns}	0.001192^{ns}	0.0000096^{ns}
Error	10	0.8852	0.002088	0.0002725
Total	17			

ns,*, **, *** = not significant, significant at 5%, 1% or 0.1%.

df = Degrees of freedom, MS = Mean squares.

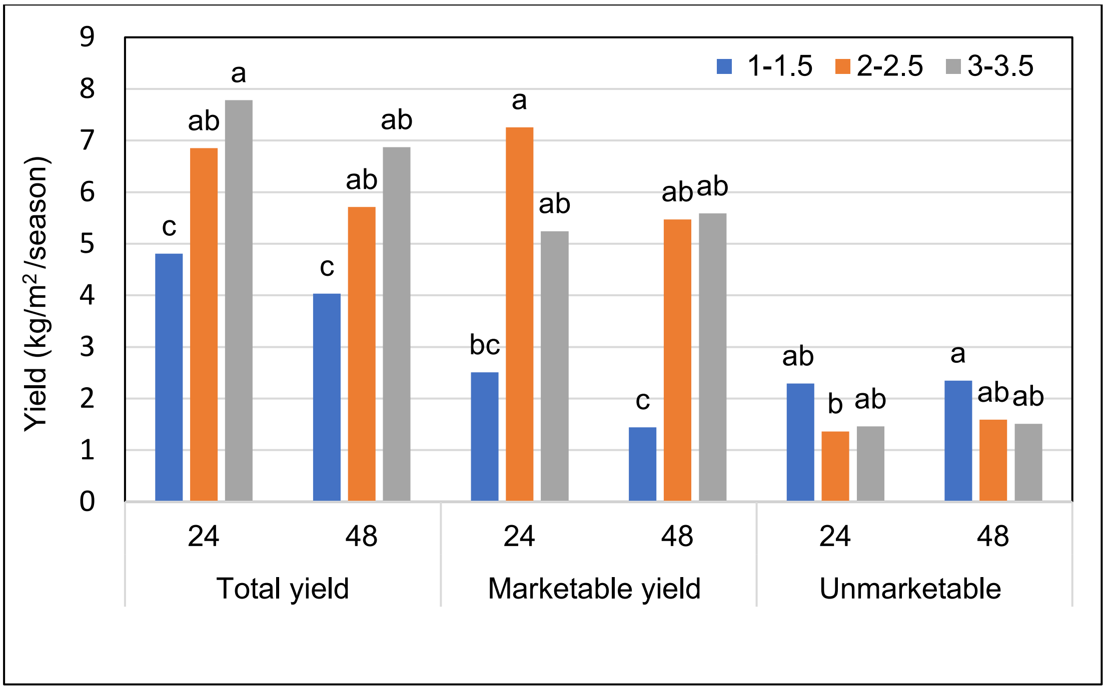

Figure 5.10: Seasonal total yield, Marketable yield and unmarketable yield of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity, water flow rate and interaction.

5.3.1.3 Crop growth and physiological disorders

The interaction between the EC and water flow rates had no significant effects on leaf area, plant height, chlorophyll and leaf area index (Table 5.4). Water flow rates did not affect growth of sweet basil on measured variables. Water stress is one of the important aspects of plant growth, hence recirculating hydroponics emphasize continuous water supply. This is to ensure water stress is completely prevented since the roots are grown in the gravel through as the growing medium. Gravel is one of the most heat absorbing media which demands high volumes of water (Niederwieser and Du Plooy, 2014). Therefore, the adjusted low supply of water in form of low flow rates indicates a positive water saving strategy. The association of the water flow rates and EC has never been established or reported before (Niederwieser and Du Plooy, 2014; Al-Tawaha et al., 2018). However, the effects of EC on growth sweet basil have been reported and confirm that sweet basil growth and yield can significantly be affect by EC concentrations (Chiloane, 2012; Walters and Curry, 2018). In this study the results demonstrated that growth parameters (plant height, leaf area and leaf area index) were comparable in the medium and highest EC concentrations. A Similar trend was reported by Walters and Curry (2018) who reported that sweet basil growth increases with an increase in EC concentrations. However, the effects of EC on growth of sweet basil still seems to be contradictory. For instance, Ciriello et al. (2020) observed that the growth of different genotypes (Aroma 2, Eleonora and Italiano Classico) of cultivar Genevose were not affected by different EC concentrations (1 mS/cm, 2 mS/cm and 3 mS/cm). Incidentally, plant height, leaf area and leaf area index were amongst plant growth variables that were not affected by those latter concentrations. Furthermore, Avdouli et al. (2021) reported that sweet basil growth in the context of plant height and branching declines with increasing EC concentration.

Table 5.4: Analysis of variance for leaf area index, plant height, chlorophyll content and leaf area affected by water flow rate, electrical conductivity and interactions in Gravel film technique system.

Source of variation	df	MS			
		Leaf area index (cm^2/cm^2)	Plant height (cm)	Chlorophyll content (SPAD)	Leaf area (cm^2)
Rep	2	0.19438	9.124	7.773	439605
Flow rate	1	0.00000^{ns}	8.172^{ns}	6.214^{ns}	6214^{ns}
EC	2	0.32041**	97.307***	343.965***	788322***
Flow rate .EC	2	0.00181^{ns}	0.558^{ns}	0.963^{ns}	27021^{ns}
Error	10	0.05544	4.773	5.915	143904
Total	17				

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%.

df = Degrees of freedom, MS = Mean squares.

Plant height of the medium concentration was higher (32 cm) than the higher (29) concentration as shown in Figure 5.11. The justification of this observation is attributed to sweet basil low tolerance of salts in higher EC concentrations. Overall, the contradiction of sweet basil response to increasing EC concentrations is attributed to the growth stage of the plant. Normally it is reported that sweet basil is a moderate feeder in the early days (1-9 days) after transplanting (Avdouli et al., 2021). The growth reduction is ascribed to decreased leaf emergence and expansion. Furthermore, sweet basil cell differentiation is intolerant to saline and nutrient imbalances that are bound in the higher nutrient concentrations. The EC concentration further affected the chlorophyll content of the sweet basil. Ideally, the higher SPAD values were observed with increasing EC concentrations (Figure 5.11b). The concentration of nitrogen is widely associated with production of more chlorophyll molecules (Albornoz et al., 2015). Therefore, lower EC concentrations tend to have low N composition, which results in yellowing of the leaves, which are indicated by low values given by the SPAD device. These, results were further confirmed by Albornoz et al. (2015) who demonstrated that chlorophyll fluorescence showed a similar efficiency of the PSII system for medium and higher EC concentrations. This confirms the light significant differences in yield and growth parameters between the treatments.

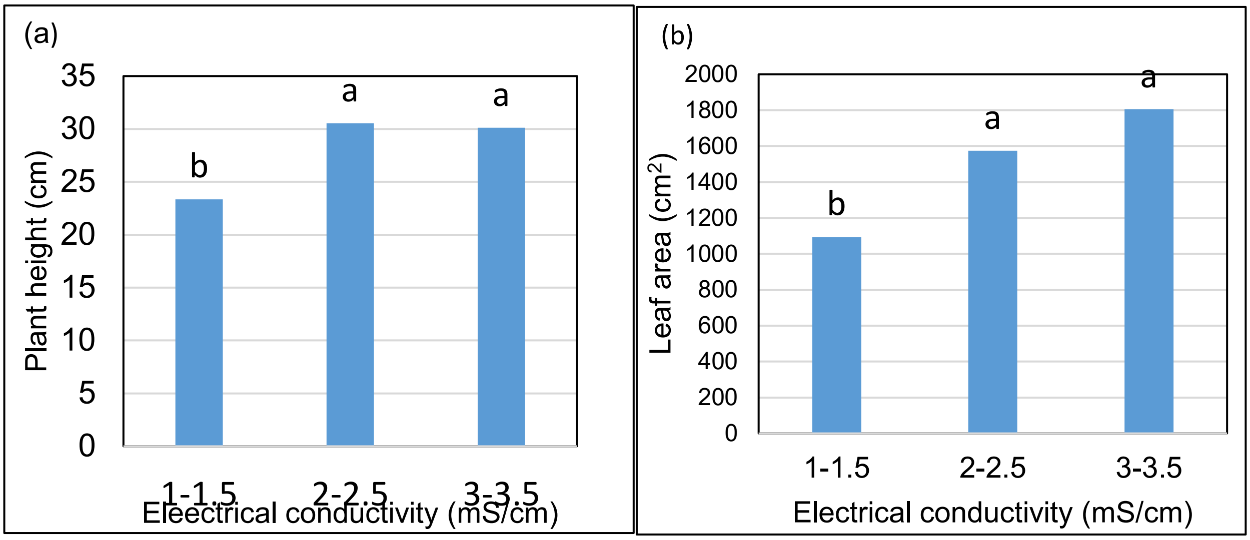

Figure 5.11: Plant height of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity (a); Leaf area of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity (b).

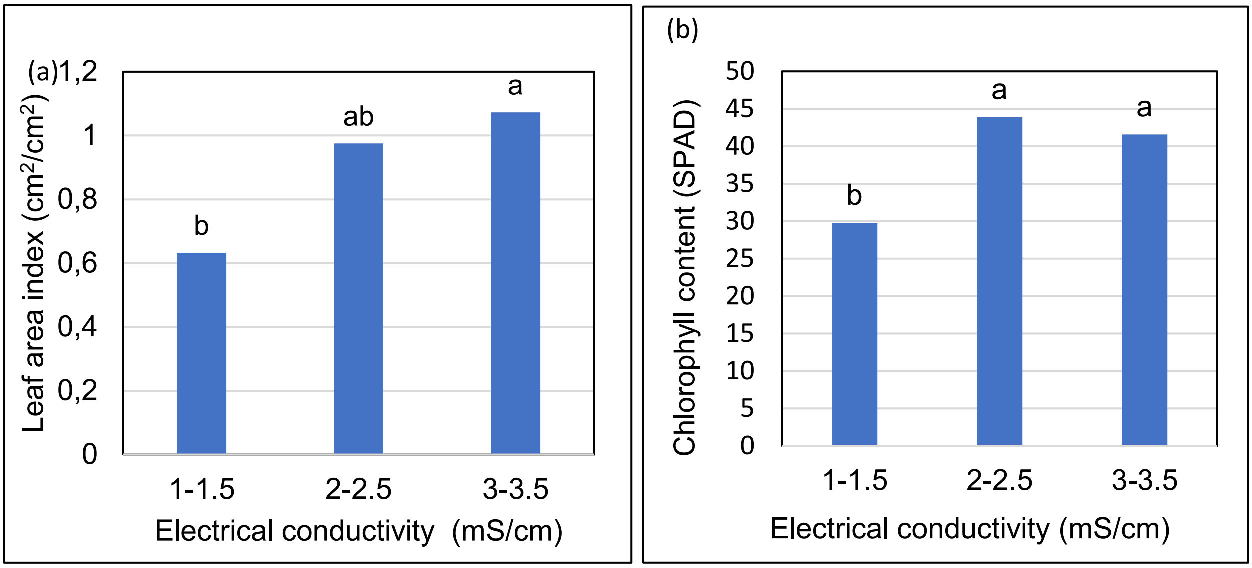

Figure 5.12: Leaf area index of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity (a); Chlorophyll content (SPAD) of sweet basil grown under a gravel recirculating hydroponic system as influence by electrical conductivity (b).

The interaction between the EC and water flow rates had no significant effects on water use efficiency (Table 5.5). However, water flow rates affected water use efficiency of sweet basil in the gravel recirculating hydroponics system. Complementary to water use, the lower water flow rate used less water and therefore was more efficient. The results demonstrate that water use efficiency was averaged at 18 and 8 kg/m^3 for 24 and 48 L/h respectively. This indicates a highly significant difference between the two water flow rates. Previous reports confirm that water flow rates affect water use efficiency in crops grown in hydroponics (Khater and Ali 2015; Al-Tawaha et al.,2018). Thus, water movement and volume in the rhizosphere should be optimized to ensure good contact time between roots and water in the system. This ensures optimal water and nutrient consumption by the plant. However, there is no significant difference amongst the EC levels on water use efficiency, but the differences between flow rates were noticeable. Higher water flow rates increased water turnover in the rhizosphere, which may have reduced oxygen in a root feeding area. Ultimately, this probably increased water stress, with consequent negative effects on water and nutrient uptake when compared to the low water flow rate. Recirculating systems can be highly successful the nutrient concentrations are balanced and water flow managed correctly in conjunction with other factors such as temperature, PH and EC. Al-Tawaha et al. (2019) reported that high water flow rates increase water volumes and depth in the rhizosphere, which may increase evaporation rates from the ground surface. Hence, the explanation for a noticeable difference between the two water flow rates tested in the present study. Furthermore, more gravel as a media could also increase evaporation and transpiration. For instance, Fayezizadeh et al. (2021) reported that tomato stomatal conductance increased with high water supply and increased temperatures. This implies that the water consumption increases with rising temperatures, and when water is supplied in abundance, plant water use efficiency is reduced. A similar finding was reported where lettuce under high temperature and water supply used water inefficiently by closing stomatal and limiting gas exchange (Fayezizadeh et al., 2021). Generally, leafy crops such as Swiss chard, Chinese cabbage have average water use efficiencies in the range of 3-5 kg/m^3 (Wenhold et al., 2012; Araya et al., 2020). The reported water use efficiency in the present study (Figure 5.13) is remarkably high when compared to drip irrigation in soil basil cultivation (1.89 kg/m^3) (Pejic et al., 2017) Recirculating hydroponics is generally reported to give rational water use efficiency (Ferreira dos Santos et al., 2019; Rosa-Rodríguez et al., 2020). For instance, Rosa-Rodríguez et al. (2020) investigated Water use efficiency of tomato in open and closed (recirculating) hydroponics, the results showed that the closed system had the highest water use efficiency (59.53 kg/m^3), whereas the open bag system had lowest (46.03 kg/m^3). Therefore, in comparison to the open system, the closed system produced 13.50 kg more fruit per cubic metre of water. Therefore, high water use efficiency values are achieved in recirculating hydroponics because water is continuously reused, which leads to minimum to no losses through drainage.

Table 5.5: Analysis of variance for Water use efficiency affected by water flow rate, electrical conductivity and interactions in Gravel film technique system.

Source of variation	df	MS Water use efficiency (kg/L)
Rep	2	3.23
Flow rate	1	362.35^{***}
EC	2	25.80^{ns}
Flow rate .EC	2	4.04^{ns}
Error	10	17.65
Total	17	

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%.

df = Degrees of freedom, MS = Mean squares.

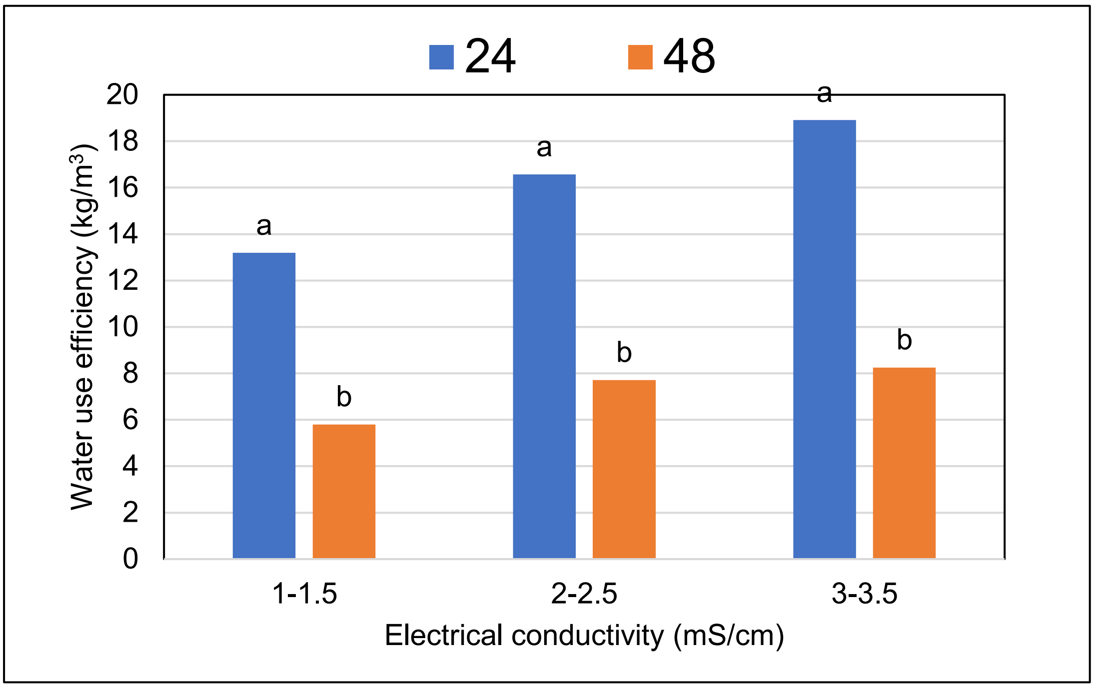

Figure 5.13: Water use efficiency of sweet basil grown under a gravel recirculating hydroponic system as influence by EC concentrations and water flow rates.

5.3.2 Lettuce experiment under a nutrient film technique

5.3.2.1 Crop water use

The highest order interaction of hydroponic structure, planting spacing and water flow had no significant difference on water use of lettuce. However, hydroponic structure and water flow had significant effects on water use of lettuce (Table 5.6). The effects show that lettuce in shade net significantly used less water (0.25 L/plant per season) and lettuce in tunnel more water (0.49 L/plant per season). Generally, this finding was expected as the experiment was conducted in a winter season.

Table 5.6: Analysis of variance for the effect of hydroponic structure, plant spacing and water flow pattern on water use of lettuce under a vertical nutrient film technique.

Source of variation	df	MS
		Crop Water use
Hydroponic structure (HS)	1	378.80***
Plant Spacing (PS)	2	2.92 ns
Water Flow (WF)	1	155.00***
PS X WF	2	0.43ns
HS X PS	2	1.83ns
HS X WF	1	22.77***
HS X PS X WF	2	0.58ns
Error	20	0.99
Total	35	

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%, respectively.

df = Degrees of freedom, MS = Mean squares.

The tunnel had temperature ranges of (16-22°C) when compared to shade net (7-17°C). According to Amitrano et al. (2021) suitable temperature for lettuce cultivations ranges from 13 to 1 8°C (Table 5.7). The increased temperature in the tunnel could be the driver of the high water consumption due to increased evaporative demand to the atmosphere. The evaporative demand is also driven by the relative humidity in the atmosphere. Amitrano et al. (2021) reported that lettuce optimum relative humidity is 97%. Relative humidity ranged 53.34% and 52.40% for shade net and tunnel, respectively. This implies that there was insufficient relative humidity in both structures for optimum growth of lettuce. According to Grossiord et al. (2020) increased temperature and low relative humidity increases plants transpiration rate. This is because leaves of the plants serve as cooling system of the plants. Therefore, Amitrano et al. (2021) reported that lettuce when is in high evaporative area could have high transpiration rate may be attributed to stomatal closure as safety mechanism in high evaporative conditions.

This may also be attributed to water flow systems that were used (intermittent and continuous water flow).

Intermittent water flow also significantly used less water when compared to continuous water flow in both hydroponics structures. Generally, crops in recirculating hydroponics (Net film technique) water flow continuously to avoid plants loss of turgid in absence growth media. However, when there is growth media is intermittent water flow (scheduled irrigation) can be introduced to reduce water use and energy. Hence, significantly less water was used in intermittent water flow when compared to continuous flow (Figure 5.14). Similar results were reported where intermittent water flow improved water use on cultivation of lettuce under recirculating hydroponics (Abou-Hadid et al., 1990). The intermittent water flow reduces water and roots contact time thereby reducing water uptake by the plants. According to (Ezziddine and Liltved, 2021) continuous flow increases exposure to evaporation due to motion in the PVC pipes.

Table 5.7: Mean monthly ambient temperatures and mean monthly relative humidity in the non-temperature-controlled tunnel during the experimental period.

	Tunnel		Shade net	
weeks	Temperature (°C)	Relative Humidity	Temperature	Relative Humidity
1	16.13	53.62	7.52	51.45
2	17.31	51.22	10.75	50.27
3	16.91	47.68	11.8	62.59
4	16.63	53.53	13.42	56.09
5	18.33	53.15	15.41	54.01
6	19.39	55.19	14.45	48.18
7	23.02	52.42	17.18	50.82
Average	18.24	52.40	12.93	53.34

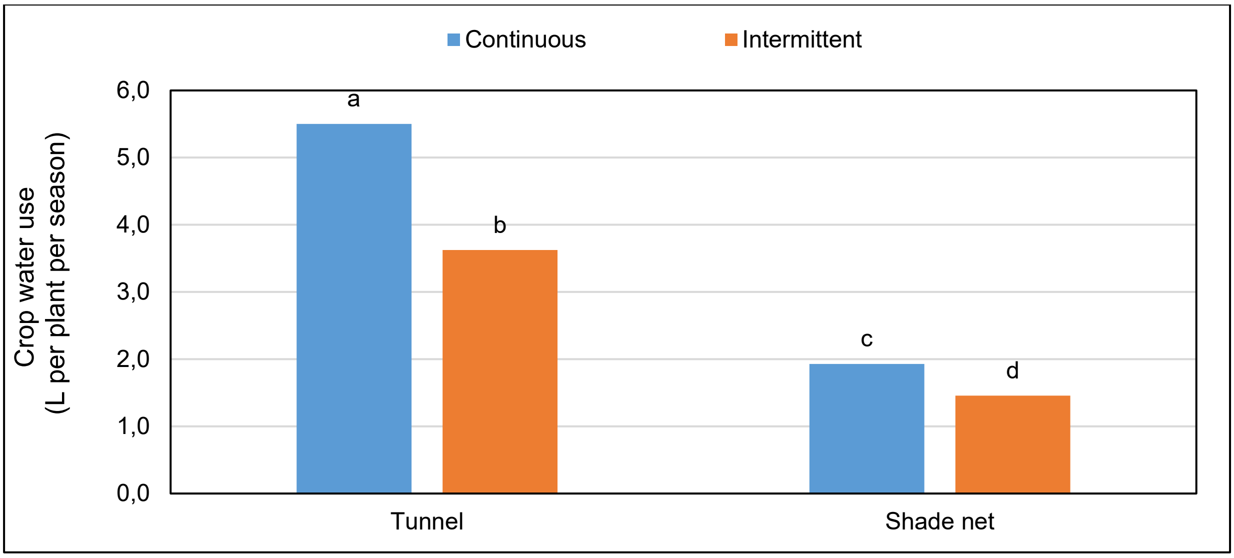

Figure 5.14: The effect of hydroponic structure, plant spacing and water flow pattern on water use of lettuce under a vertical nutrient film technique.

5.3.2.2 Marketable yield

The interaction between hydroponic structure, plant spacing and water flow did not affect yield per plant and yield per unit area. The interaction between planting spacing had a significant effect on yield per plant (P=0.05) yield per unit area (P=0.01) (Table 5.8). The results demonstrate that tunnel structure produced more marketable yield (0.211 kg) when compared to shade net (0.11 kg). This may be attributed to the environmental variations, the tunnel provided optimum temperature for maximum biomass production at an average of 18.24°C, whereas the shade net was below the optimum 12.93°C. (Amitrano et al. (2021). Optimum temperature helps the crop perform its morphological and anatomical processes such as stomatal opening and closure. The stomatal opening helps facilitate smooth photosynthesis process. As a gate keeper for loss of water through transpiration and uptake of carbon dioxide. Carbon dioxide plays a pivotal role in assimilation production. Low temperatures generally affect crops water and nutrients uptake (Chiloane, 2012). Thakulla et al., 2021 investigated the effects of solution temperature on biomass production of lettuce in a recirculating hydroponics system. The results demonstrated that high temperature solution (26°C) increases the amount of oxygen (9.3 mg/L) in the solution. In contrast low temperature solution (24°C) reduced oxygen (6.2 mg/L) in the root zone. Therefore, this suggests that the root decreased ability to uptake sufficient water and nutrients may be due to decreased level of oxygen in the solution due to low temperatures (Thakulla et al., 2021).

Table 5.8: Analysis of variance for the effect of hydroponic structure, plant spacing and water flow pattern on lettuce marketable yield per plant and per unit area under a vertical nutrient film technique.

Source of variation	df	MS	
		Yield per plant	Yield per unit area
Hydroponic structure (HS)	1	0.00733021***	58.972910***
Plant Spacing (PS)	2	0.01342950***	753.782521***
Water Flow (WF)	1	0.00065451ns	6.089103*
PS X WF	2	0.00085818ns	1.942149ns
HS X PS	2	0.00159561*	16.211673***
HS X WF	1	0.00011990 ns	0.283604ns
HS X PS X WF	2	0.00033117ns	1.631268ns
Error	20	0.00737775	1.000000
Total	35		

ns, *, **, *** = non-significant, significant at 5%, 1% or 0.1%, respectively.

df = Degrees of freedom, MS = Mean squares.

Oxygen in the root zone is important for root respiration and ultimate growth. The inhibition or slowness of nutrient uptake stress plants metabolism as important macro and micro mineral elements are not sufficient in the leaves. Thus, yield of the crop is reduced. However, the effects of planting density were similar in both tunnel and shade net. The spacing 10 cm had the highest yield and the spacing 30 cm had the lowest yield (Figures 5.15 and 5.16). Incidentally, similar results were reported previously where high density increases yield on lettuce (Maboko and Du Plooy, 2009) and sweet basil grown in recirculating hydroponics (Maboko and Du Plooy, 2013). Generally, in soil-based production the high density reduces yield when compared to low dense population. Research based on soil-based production reports that this is due to competition for nutrients in the soil brought by high planting density. This suggests that the uniform supply of nutrients in recirculating hydroponics nullifies the competition of nutrients in soil production. Furthermore, competition for radiation in the high dense population also enhances biomass production due to constant supply of nutrients. Hence there is low yield in low dense population (Maboko and Du Plooy,2009; 2013).

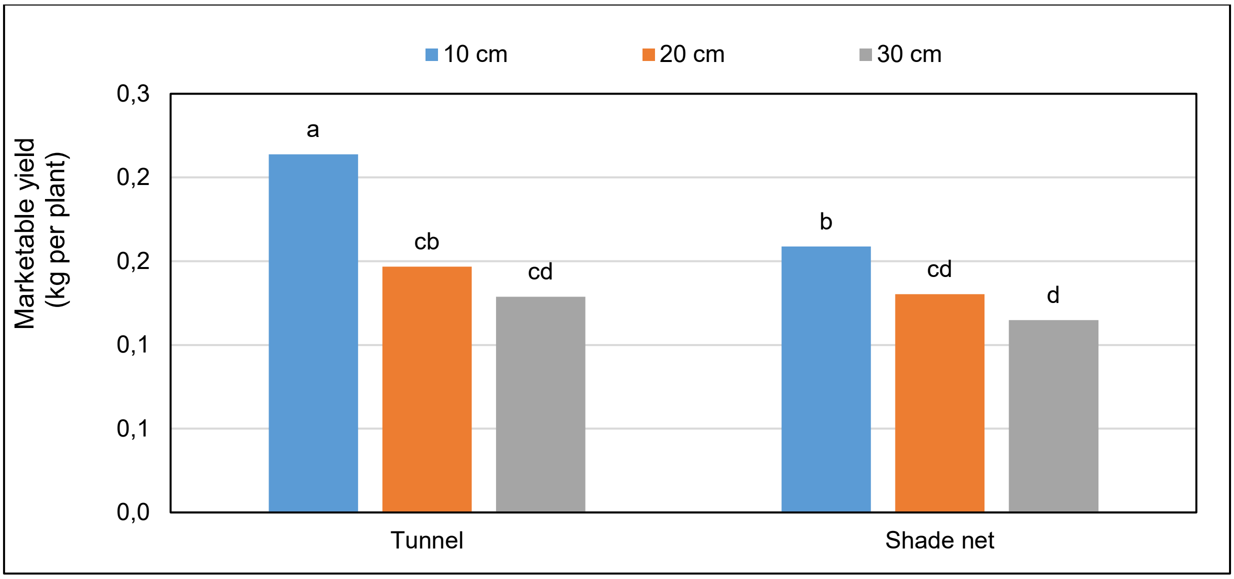

Figure 5.15: Lettuce marketable yield per plant under different hydroponic structured and plant spacing.

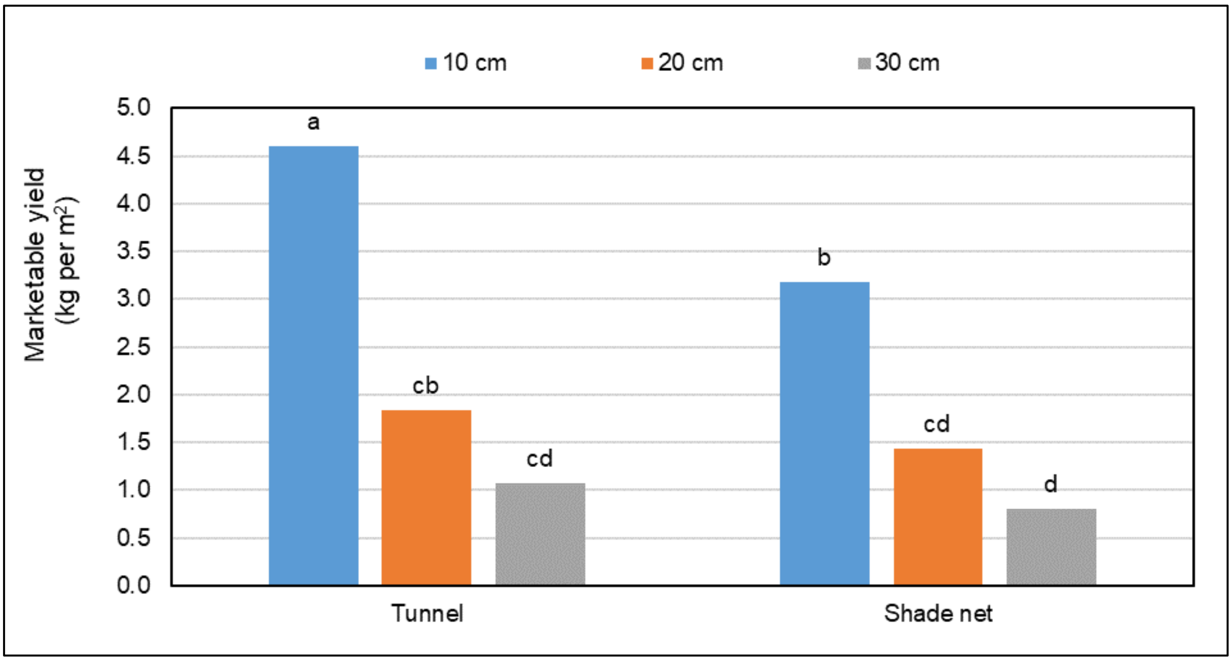

Figure 5.16: Lettuce marketable yield per unit area under different hydroponic structured and plant spacing.

5.3.2.3 Crop growth

The interaction of hydroponic structure, planting spacing and water flow had no significant effects on Leaf area per plant, plant width, root mass and root length (Table 5.9). However, the interaction hydroponic structure and plant spacing had significant effects on Leaf area per plant (P= 0.05) and root mass (P = 0.01). The leaf area per plant and root mass coincides with the yield biomass production. The consistency is apparent with previous studies where high planting density reported to increase light use efficiency in hydroponics plants. In hydroponics significant number of plants growing in a unit area might have strived for more sunlight, thereby inducing stem elongation and leaf expansion (Maboko and Du Plooy, 2013). For instance, Amoozgar et al. (2017) studied the effects of different lights (LEDs) (white, red and blue) on growth and yield of lettuce. The results suggested that blue LEDs seem to stimulate leaf area enlargement and the aboveground development of lettuce. Li et al. (2020) reported that plants in hydroponics use the light pigment harvesters from the Xanthophyll molecule to increase light use efficiency for photosynthesis. Xanthophyll is a set of molecules in a cycle with main function is to protect plants against oxidative stress that may be generated by high-light intensity. The cycle is said to work normally under favourable conditions however light competition may trigger increase in efficiency (Li et al., 2020; Genty et al., 1989).

The effects of root mass are comparable shade net, and, in the tunnel, this finding is contradictory to the yield output of the two hydroponics structures. Interestingly the 30 cm spacing has the highest root mass, which furthers the contradiction of the findings. However, according Thakulla et al. (2021) reports that plant stress induced by the low temperature in the solution may impedes translocation of minerals into the leaves. Furthermore, root elongation may be use to excessive space in the root due to less population in the 30 cm plants. For example, the plant density in the 10 cm spacing was 20 plants/m^2, 20 cm spacing was 10 plants/m^2 and 30 cm was 7 plants/m^2. This shows that the lowest planting density had enough space to grow and elongate than in dense population provided they receive equal amounts of nutrients.

Table 5.9: Analysis of variance for the effect of hydroponic structure, plant spacing and water flow pattern on lettuce growth parameters under a vertical nutrient film technique.

Source of variation	df	MS			
		Leaf area per plant	Plant width	Root mass	Root length
Hydroponic structure (HS)	1	29605605***	338.77 ***	2.80 ns	0.84 ns
Plant Spacing (PS)	2	182372*	0.37 ns	0.19 ns	2.45 ns
Water Flow (WF)	1	60846ns	038 ns	3.62 ns	5.02*
PS X WF	2	32352ns	0.26 ns	2.13 ns	0.22 ns
HS X PS	2	134082*	0.03 ns	6.61 **	2.62 ns
HS X WF	1	19337ns	0.03 ns	1.66 ns	2.78 ns
HS X PS X WF	2	33438ns	0.41 ns	1.30 ns	0.94 ns
Error	20	43483	1.00	19.99	1.0
Total	35				

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%, respectively.

df = Degrees of freedom, MS = Mean squares.

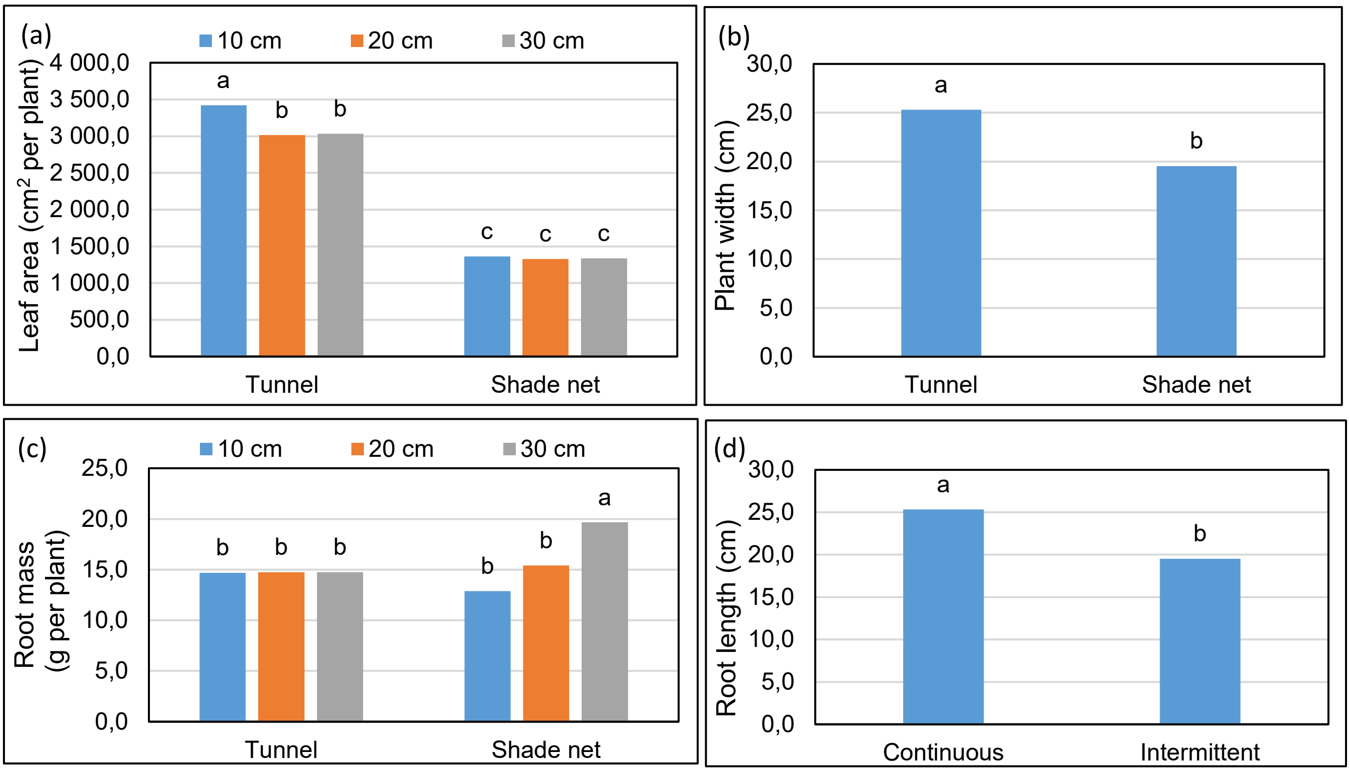

Figure 5.17: Growth parameters of lettuce grown under different hydroponic structures and plant spacing.

5.3.2.4 Crop physiological response

The highest order of interaction of hydroponic structure, plant spacing and water flow had no significant effects on the leaf chlorophyll content and leaf stomatal conductance of lettuce (Table 5.10). The first order of interaction also had no significant effect on leaf chlorophyll content and stomatal conductance. However, hydroponic structure had significant effects on leaf chlorophyll content and leaf stomatal conductance (Li et al., 2020). Water flow also affected stomatal conductance (Figure 5.18). These are important physiological parameters that give important information on the anatomy of the plant (Rosa-Rodríguez et al., 2020). Chlorophyll content is expected to be uniform amongst treatment because nutrients were supplied uniformly. However, the hydroponics structures demonstrate that chlorophyll content was reduced in shade net. This may be due to low temperatures experienced in shade net (Li et al., 2020). Low temperature has been reported to reduce or impede nutrients elements such as nitrogen, magnesium and potassium. Chiloane, 2012 reported that lower chlorophyll content may be due to leaf deficiency of important minerals such as nitrogen and magnesium. Deficiency of minerals such as nitrogen affects plants' normal metabolic activities. Nitrogen metabolic functions include chlorophyll molecules formation, new cell formation and protein synthesis (Inoue et al., 2021). Similarly, stomatal conductance is the measure of the molar flux of carbon dioxide entering the leaf and net water exiting the leaf pores through transpiration. The results demonstrate that high stomatal conductance was released in tunnel (147 mmol m^{-2} s^{-1}) when compared to shade net (134 mmol m^{-2} s^{-1}). The function is facilitated by opening and closing of a stomata. Therefore, stomatal closure reduces gas exchange and transpiration. Thus, the assimilation production will be negatively affected due to lack of carbon dioxide (Genty et al., 1989). Ultimately stomatal conductance values will be low as in the shade net. Low relative humidity which is the atmospheric water content can also suppress the photosynthetic performance of lettuce directly impairing metabolic activities including the enzyme activity of Calvin-Benson cycles (Inoue et al., 2021) and leads to the loss of biomass production throughout the crop growing period.

Table 5.10: Analysis of variance for the effect of hydroponic structure, plant spacing and water flow pattern on lettuce leaf chlorophyll content and stomatal conductance under a vertical nutrient film technique.

Source of variation	df	MS	
		Leaf chlorophyll content	Leaf stomatal conductance
Hydroponic structure (HS)	1	24.19 ***	1191.16***
Plant Spacing (PS)	2	0.03 ns	125.26 ns
Water Flow (WF)	1	1.98 ns	1208.16 ***
PS X WF	2	0.08 ns	9.98 ns
HS X PS	2	2.20 ns	96.35 ns
HS X WF	1	2.91 ns	429.83 ns
HS X PS X WF	2	0.55 ns	107.88 ns
Error	20	1.00	142.69
Total	35		

ns, *, **, *** = not significant, significant at 5%, 1% or 0.1%, respectively.
df = Degrees of freedom, MS = Mean squares.

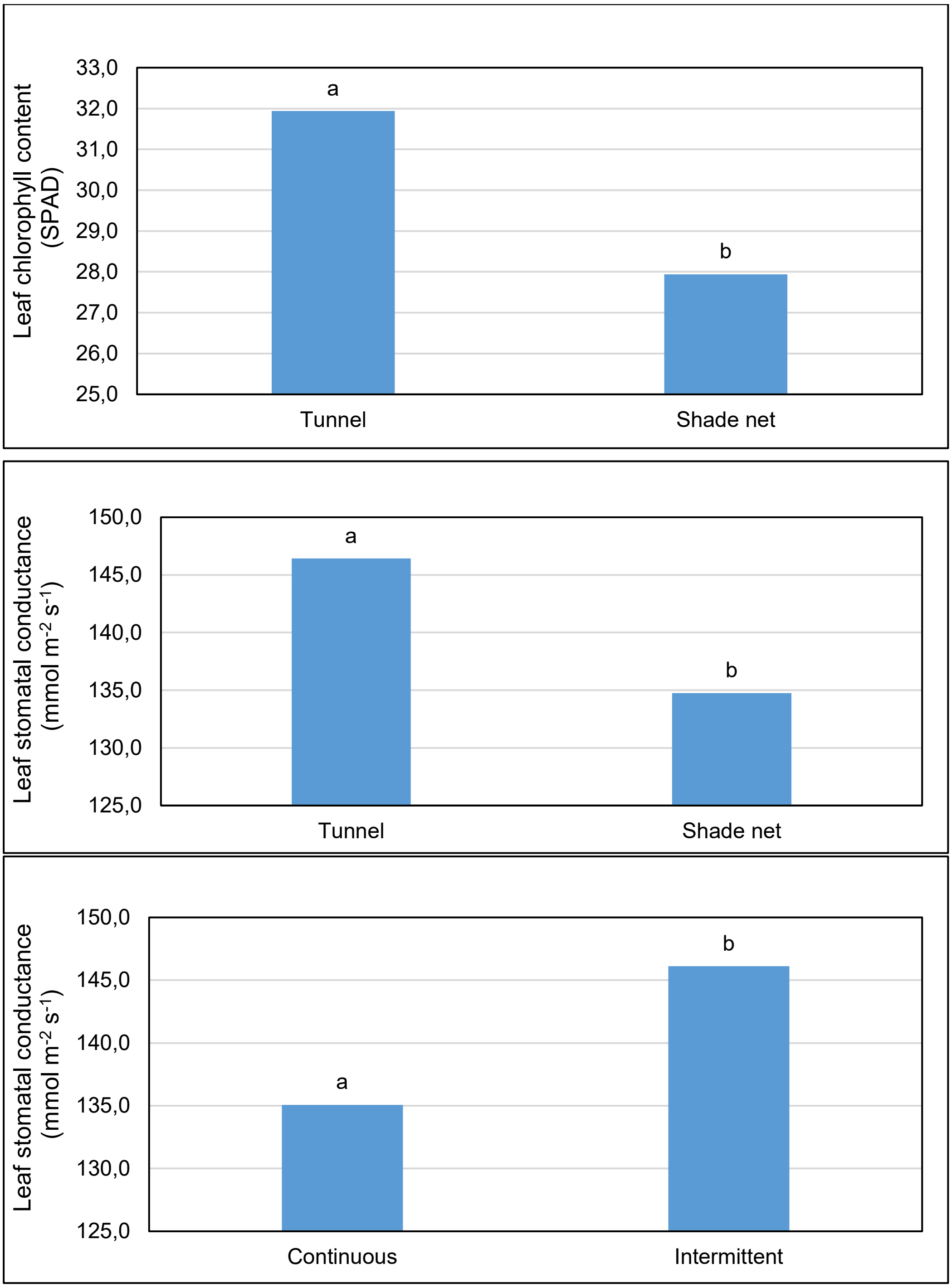

Figure 5.18: Plant physiological parameters of lettuce grown under different hydroponic structures and plant spacing.

5.3.2.5 Water use efficiency

The highest order of interaction of hydroponic structure, plant spacing and water flow had no significant effects on the water use efficiency of lettuce (Table 5.11). However, all (spacing x water flow; hydroponics structure x plant spacing; hydroponic structure x water flow) the first order of interaction had significant effects plant had significant (P = 0.05) effects on water use efficiency of lettuce. The results demonstrate that water use efficiency was high in the shade net when compared to the tunnel (Figure 5.19a). This may be due to low water uptake in the shade net due to below optimal temperature requirements. According to Chiloane (2012) Lettuce could be a winter crop but cannot withstand temperatures below 12°C. However, water use efficiency is the amount of biomass produced per unit water used (Michelon et al., 2020). Therefore, the objective to have high yield with low water use. Thus, although there was low water use efficiency in tunnel (0.06 kg/L) when compared to shade net (0.11 kg/L). Environmental conditions that enhanced more biomass production is endorsed. However, generally hydroponic based cultivations have to be reputable in terms of water use efficiency when compared to soil-based cultivations. For instance, Michelon et al. (2020) investigated different water regimes on production of lettuce. The results demonstrated that average water use efficiency in soil cultivation at 0.04 kg/L. Furthermore, related to lettuce production, Barbosa et al. (2015), directly compared lettuce grown on soil and in recirculating hydroponics and found water use efficiency of 0.004 and 0. 05 kg/L. Hydroponics high value water use efficiency is attributed to recirculating nature of the system. The systems literally save and reuse water that was meant to drain in the soil basil agriculture (Barbosa et al., 2015). Moreover, intermittent water flow was also more efficient when compared to the continuous water flow. The scheduled water flow also increases water use efficiency (Rosa-Rodríguez et al., 2020). It is reported that plants in NFT with continuous may experience shortages of oxygen. Therefore, intermittent water flow helps the crops to absorb oxygen when water flow is off. Oxygen helps plants in anabolic respiration and may also prevents root rots due to excessive water in the root zone (Vandam et al., 2017).

Table 5.11: Analysis of variance for the effect of hydroponic structure, plant spacing and water flow pattern on water use efficiency of lettuce under a vertical nutrient film technique.

Source of variation	df	MS
		Crop water use efficiency
Hydroponic structure (HS)	1	0.01744144***
Plant Spacing (PS)	2	0.00298259 ***
Water Flow (WF)	1	0.00382838 ***
PS X WF	2	0.00023582 *
HS X PS	2	0.00024118 *
HS X WF	1	0.00022150 *
HS X PS X WF	2	0.00007529 ns
Error	20	0.00006139
Total	35	

ns, *, **, *** = non-significant, significant at 5%, 1% or 0.1%, respectively.

df = Degrees of freedom, MS = Mean squares.

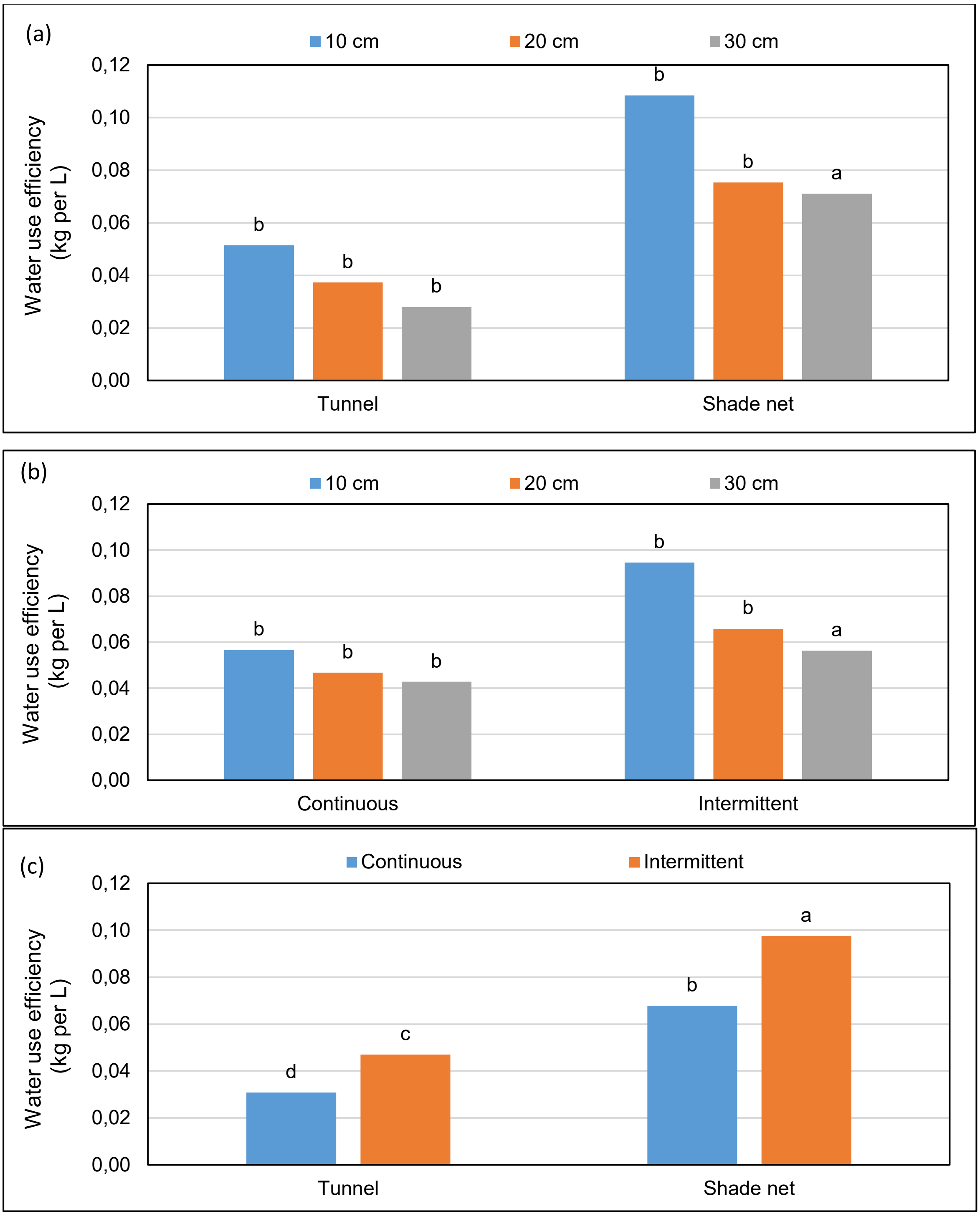

Figure 5.19: Water use efficiency of lettuce grown under different hydroponic structures and plant spacing, as influenced by: (a) an interaction between plant spacing and hydroponic structure; (b) an interaction between plant spacing and water flow pattern and (c) an interaction between water flow pattern and hydroponic structure).

5.4 Conclusions and recommendations

Sweet basil performed best in terms of marketable yield, water use and WUE under a water flow rate of 24 L/hr and EC levels of 2.0-2.5 mS/cm. Sweet basil is tolerant to increasing EC concentrations. Sweet basil production under shade may be affected negatively by rainfall. Therefore, there is a need to implement preventative spraying to control fungal diseases.

Vertical farming is a promising hydroponic technique for increased crop yields particularly when the systems are operated under a tunnel. The increased ambient temperature, heat and humidity inside the plastic tunnel accelerates crop growth, which leads to increased yield. In addition, plants growing under a plastic tunnel are protected from harsh environmental conditions such as extreme cold and radiation, heavy rains and strong wind, which results in higher marketable quality of fresh produce. However, the environmental conditions around the tunnel are conducive to increased crop water use, which leads to decreased water use efficiency. Nonetheless, recirculating hydroponic systems are generally water savers, since there is no drainage through the system. Farmers are encouraged to plant leafy greens and herbs at high densities with narrow spacing, in order to maximize crop productivity. It is however recommended that cost-benefit analysis be conducted to evaluate the application of tunnel versus shade net use in hydroponics, so that a more informed decision can be provided to farmers in terms of the most suitable type of hydroponic structure to be used in vertical farming.

Farmers are encouraged to plant leafy greens and herbs at high densities with narrow spacing, in order to maximize crop productivity. It is however recommended that cost-benefit analysis be conducted to evaluate the application of tunnel versus shade net use in hydroponics, so that a more informed decision can be provided to farmers in terms of the most suitable type of hydroponic structure to be used in vertical farming. Appropriate agronomic practices for horizontal gravel film hydroponic systems are necessary to increase resource use efficiency, thus contributing to increased income generation of farmers, improved food security and sustainable livelihoods.

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CHAPTER 6: ON-FARM EVALUATION OF BEST HYDROPONIC PRACTICES USING NFT, GFT AND HYDROPONICS PLANTER

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6.1 Introduction and background

Recovery or recirculating hydroponic systems (those which rely on pumps to actively move the nutrient solution to the planting bed, with the remaining nutrients after root uptake being recovered and reused in the system) are well known for their potential to maximize crop production, resulting in increased yields and better quality of the produce (Maboko and Du Plooy, 2009; Maboko et al., 2011; Maboko and Du Plooy, 2012; Maboko and Du Plooy, 2013a; Maboko and Du Plooy, 2013b; Maboko and Du Plooy, 2013c; Maboko et al., 2017; Maboko and Du Plooy, 2018; Mampholo et al., 2018; Araya and Moremi, 2021; Moremi and Araya, 2021). Such systems are able to sustain crop production continuously throughout the year, using controlled environmental fluctuation techniques, thus limiting or eliminating the influence of harsh weather conditions. In addition, hydroponic production is generally less labour intensive, since it does not require cultural operations, such as ploughing, weeding and soil fertilization. These systems can also be put up anywhere near the markets and, as a result, the fresh produce can have better marketable qualities due to reduced transportation distances, especially for highly perishable vegetables. Compared to conventional soil cultivation methods, hydroponic systems are generally more efficient in terms of land, water and nutrient use, and are often less susceptible to the incidence of pests and diseases due to lower crop exposure to environmental stresses (Treftz and Omaye, 2015). In such systems, crops can be produced on non-arable land, including poor soils having high salinity levels (Putra and Yuliando, 2015).

Recovery hydroponic systems, such as the gravel and nutrient film techniques are the most used, not only in South Africa (Maboko and Du Plooy, 2009; Maboko et al., 2011; Maboko and Du Plooy, 2012; Maboko and Du Plooy, 2013a; Maboko and Du Plooy, 2013b; Maboko and Du Plooy, 2013c; Maboko et al., 2017; Maboko and Du Plooy, 2018; Mampholo et al., 2018; Araya and Moremi, 2021) but worldwide (Runia and Amsing, 2001; Raimondi et al., 2006). In the gravel film technique (GFT), plants are particularly grown in gravel, which is a well-drained inorganic substrate; whereas, in the nutrient film technique (NTF), plants can be grown in both organic (mostly cocopeat system, while clay pebble) and inorganic substrates (mostly perlite and Rockwool), with the main difference being that in the former the nutrient solution is continuously recirculated through the system, while in the latter the nutrient solution can be recirculated continuously or intermittently as a result of higher water holding capacity of the substrates utilized for production. Recirculation of water on a regular basis, as opposed to a continuous water flow, may be an advantage for the improved nutritional content of the crop, especially for fruiting vegetables like strawberries and cherry tomatoes, however, it requires a more complex system set-up, involving a timer to regulate water cycles based on crop water requirements. The GFT is often implemented horizontally, while the nutrient film technique is conducted both horizontally and vertically. Both techniques are most suitable for the production of leafy crops under protected environmental conditions. In 2017, Maleka and Pule (2019) introduced another recirculating system in South Africa, called "vertical hydroponics planter". The system combines the advantages of optimization of space, water use and energy consumption. The GFT, NFT and hydroponics planter systems were introduced to South African farmers through the implementation of the WRC-funded project C2019/2020-00229.

6.1.1 Study aim and objectives

The aim of this study is to evaluate the performance of the three hydroponic technologies introduced at farmers' sites, in terms of systems design, crop productivity and major challenges and opportunities identified by farmers.
The following objectives were formulated:

- To verify performance of the developed/ improved technologies under farmers' conditions;
- To provide feedback to station researchers on the performance of the on-station developed/ improved technologies in the farmers' fields;
- To achieve farmers participation in the development, testing and evaluation of technologies developed/ improved on-stion.

6.1.2 Problem statement

The conditions of crop production on the farms are different from those experience at research station. This is particularly important in hydroponics, as the system requires intensive monitoring, adequate sanitation measures and continuous supply of an energy source. While these conditions are greatly met at a station level, challenges may be encountered at a farm level. Therefore, there is a need to verify the performance of developed/ improved technologies under farmers' conditions. This will assist in identifying technology limitations to achieve farmer-researcher participatory solutions.

6.2 Methodology

6.2.1 Description of the study sites

The GFT, NFT and hydroponics planter systems were tested in the West Rand District Municipality (Western region) of Gauteng Province, during the 2022-2023 growing season. Experimental research sites were established at three farmers' sites: (1) Zuurbekom Town (Mme Mbatha located at 26° 18'' 03" S and 27° 45' 08" E and Mme Zodwa located at 26° 18'' 52" S and 27° 44' 46" E) and (2) AB Farms located at Westonaria Agripark, portion 34 of Gemspost (26° 16'' 42.6" S and 27° 40' 53.8"), as shown in Figure 84.

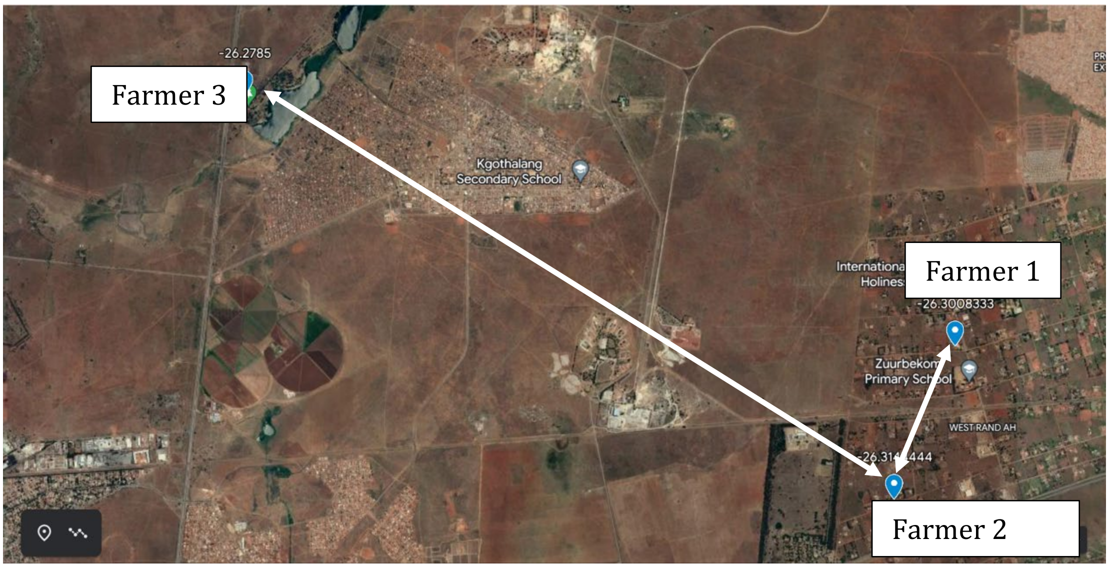

Figure 6.1: Location of the study sites in the Western region of Gauteng Province.

All three experimental sites were located within the summer rainfall area of South Africa, which experiences a mild subtropical highland climate that is neither humid nor too hot. The Western region has a mean annual temperature of 17.9°C, relative humidity of 54.1% and reference evapotranspiration of 1315.9 mm. The monthly average values for maximum and minimum temperature and relative humidity, as well as monthly totals of grass reference evapotranspiration (ETo) during spring and summer growing seasons, for the past 15 to 19 consecutive years of historical data are presented in (Table 6.1).

Table 6.1: Monthly average solar radiation (Rs), maximum (Tmax) and minimum (Tmin) air temperatures, maximum (RHmax) and minimum (RHmin) relative humidity, as well as monthly total reference evapotranspiration (ETo) over a long-term period of 15 to 19 consecutive years (2000/2004 to 2019).

Month	Atmospheric variability					
	Rs (MJ m-2 d-1)	Tmax (oC)	Tmin (oC)	RHmax (%)	RHmin (%)	ETo (mm month-1)
October	21.53	29.47	11.01	74.69	19.83	141.89
November	22.54	29.57	12.86	79.53	25.01	143.97
December	21.15	29.84	15.1	84.79	32.87	140.9
January	22.04	30.52	15.51	85.19	31.85	145.29
February	19.15	30.22	14.62	90.04	33.61	114.27
March	17.12	28.44	12.77	89.94	34.68	109.82

6.2.2 Hydroponic systems design

At Mme Mbatha trial site, a complete GFT system was installed, under a non-temperature-controlled plastic tunnel covered with a 60% white shade net on top (Figure 6.2). The plastic tunnel is equipped with opening and closing flaps in front and end sides. The flaps are tied with a rope that is supported by a roller at the top of the tunnel to facilitate the opening and closing of flaps. The 60% white shade net covers the length sides of the plastic tunnel to reduce temperature and increase durability of the structure. The 300 m^2 (30x10 m) hydroponic structure consisted of five hydrolines (1.5 m wide x 28 m long). Each hydroline is 6 cm deep, covered by 250-micron black plastic at the bottom and filled with 8-13 mm diameter gravel stones (Figure 6.3).

Figure 6.2: A completed GFT system installed at Mme Mbatha trial site in Zuurbekom, West Rand District Municipality. The GFT system uses an electrical

source to pump the nutrient solution to the top of the hydrolines, and thereafter, the excess nutrient solution flows back into the reservoir through gravity.

Figure 6.3: Components of the GFT system installed at Mme Mbatha's site: electrical system (a), hydrolines showing a gravity water flow pattern (b), municipal water source (c) and nutrient solution reservoir (d). The system is connected to a 5000-L JoJo tank, which contains a 1.1 kw submersible pump delivering 1650 litres of nutrient solution per hour.

Figure 6.4: Hydroline characteristics: 6 cm deep, covered by 250 micron black plastic at the bottom and filled with 8-13 mm diameter gravel stones.

The GFT nutrient mixing area is composed of a 35 cm deep x 55 cm wide x 75 cm long mixing tank built of concrete (Figure 6.5a). (Figure 6.5a) illustrates three types of inorganic soluble fertilizers (Hygroponics, Calcium Nitrate and Potassium Nitrate) which are needed to meet nutrient requirements of a fruity crop like tomato during the reproductive phase. The nutrients are mixed separately first, before adding them into the mixing area and prior to that, the pH of the water is adjusted to the suitable range (5.5-6.5) using Nitric Acid. Similarly to pH, the electrical conductivity (EC) of the nutrient solution is set to a suitable range using an EC/pH combo meter (Figure 6.5b).

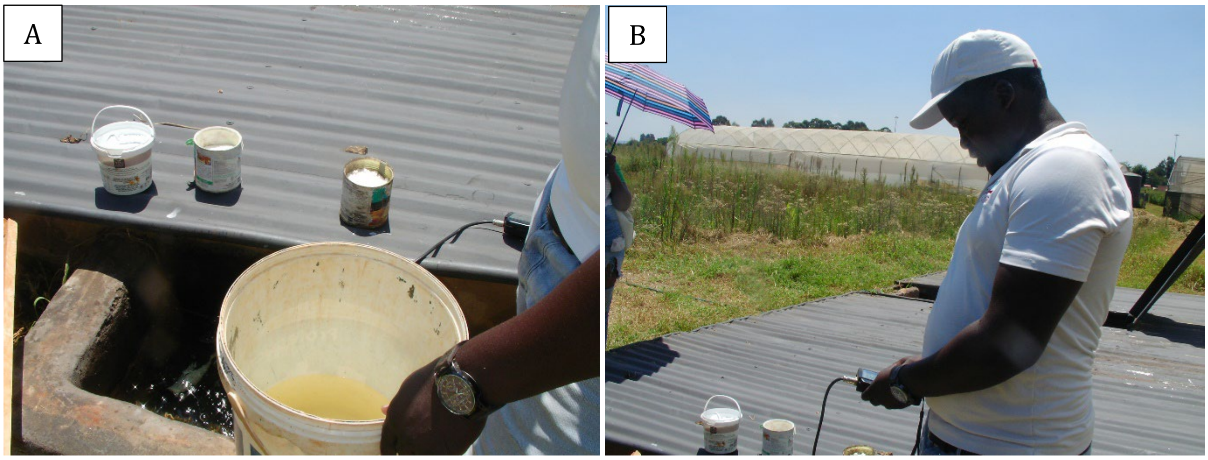

Figure 6.5: The GFT nutrient solution mixing area: inorganic soluble fertilizers ready to be added into the system (a) and an EC/pH combo meter being used to make suitable adjustments of the nutrient solution (b).

At Mme Zodwa trial site, a complete NFT system was installed, under a non-temperature-controlled plastic tunnel covered with a 60% white shade net on top (Figure 6.6). The plastic tunnel is equipped with side rollers on the length sides that extend from front to the end. The plastic is rolled with a steal bar connected to a steak handler. The 300 m^2 (30x10 m) hydroponic structure consisted of five A-frames (6.0 m long x 0.8 m wide x 2.2 m high, accommodating 14 stacked growing layers).

Figure 6.6: A completed NFT system installed at Mme Zodwa trial site in Zuurbekom, West Rand District Municipality. The farmer (first on the left) and the hydroponics team (remaining participants on the right) celebrating the great achievement.

The NFT system uses an electrical source to pump the nutrient solution to the top of the A-frames (Figure 6.7a), and thereafter, the excess nutrient solution flows back into the reservoir through gravity. The system is connected to a 260-L JoJo tank containing a 40w submersible fish pond pump which delivers 1800 L of nutrient solution per hour to the A-frames (Figure 6.7b). The 260-L tank is connected to a 0.78 kw pool pump that refills water at a rate of 3000 litres per hour from a 5000-L water tank (Figure 6.7c). Municipal tap water is used to fill up the 5000-L water tank (Figure 6.7d).

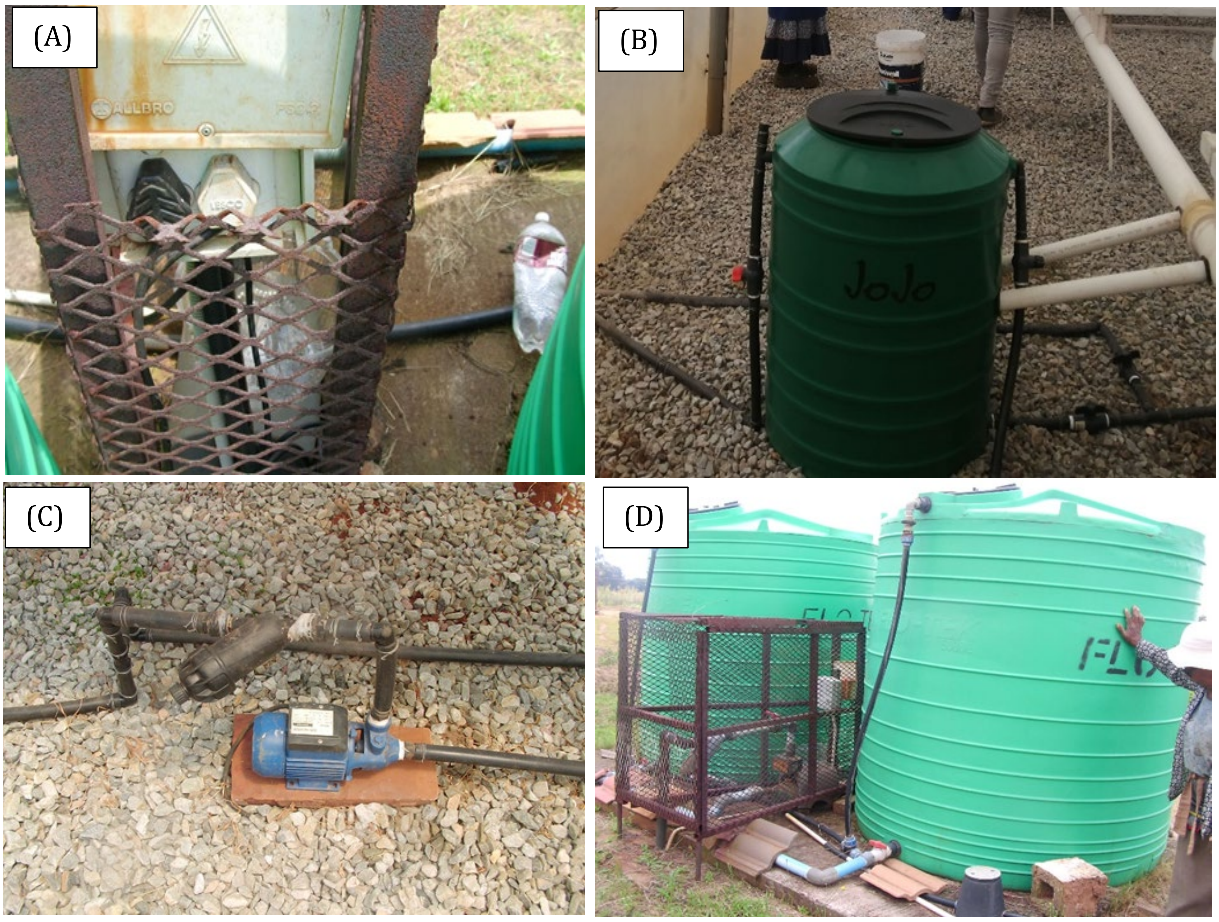

Figure 6.7: Components of the NFT system installed at Mme Zodwa's site: electrical system (a), 260-L tank (b), surface centrifugal pump (c) and 5000-L tank (d).

The NFT system at Mme Zodwa's site is equipped with a seedling production nursery at the bottom of the A-frame structure (Figure 6.8). The nursery is 6 m long x 0.8 m wide and is equipped with nine sprayers spaced at 70 cm apart. The structure the capacity to accommodate 12 trays of 200 seedlings each, giving a total of 2400 seedlings at once.

Figure 6.8: A seedling production nursery built at the bottom of the A-frame structure at Mme Zodwa's trial site.

At AB Farms trial site, a complete vertical hydroponics planter system was installed under a 300 m^2 temperature-controlled plastic tunnel. The structure accommodates up to 10 000 planters. The vertical hydroponic structure is 2.5 m high, 10 m wide and 27 m long (Figure 6.9).

Figure 6.9: A complete vertical hydroponic system installed at AB Farm's trial site.

6.2.3 Seedling production

Seedlings of leafy vegetables and herbs can be produced directly in net cups through direct seeding or through the conventional way using polystyrene trays (Figure 6.10). Sowing directly in net cups is an innovative method introduced to farmers. In this method, 80% of the growth media is composed of cocopeat, 15% Hygromix and 5% vermiculite. This method results in considerable savings to the farmer, since it uses very little Hygromix unlike the conventional method of producing seedlings.

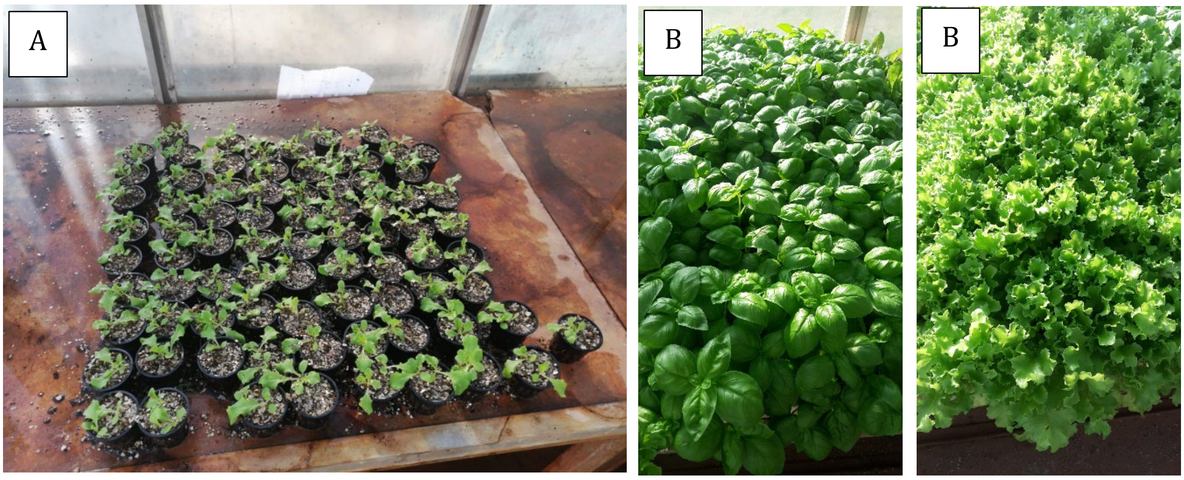

Figure 6.10: An innovative seedling production method through direct seeding in net cups (a) and conventional method in polystyrene trays for sweet basil (b) and lettuce (c) seedlings.

6.2.4 Postharvest handling

Fresh leafy vegetables and herbs are harvested, washed with clean tap water, packaged and stored in a cold environment for increased shelf life (Figures 6.11a-d, respectively).

Figure 6.11: Fresh lettuce heads being harvested at Mme Zodwa's site (a), washed with clean tap water (b), packaged as living lettuce (c) and stored in a cold environment for increased shelf life and marketable quality (d).

6.3. Results and discussion

6.3.1 Gravel Film Technique – Mme Mbatha's site

6.*3.1.1 Environmental variability inside the hydroponic structure*

Hourly ambient temperatures inside the non-temperature-controlled plastic tunnel at Mme Mbatha's site fluctuated between 10 (night-time) and 50 degree Celsius (daytime). Hourly ambient relative humidity reached extremely low values (close to zero) particularly during night-time hours. Relative humidity values below 30% and above 60% can be detrimental to crop growth.

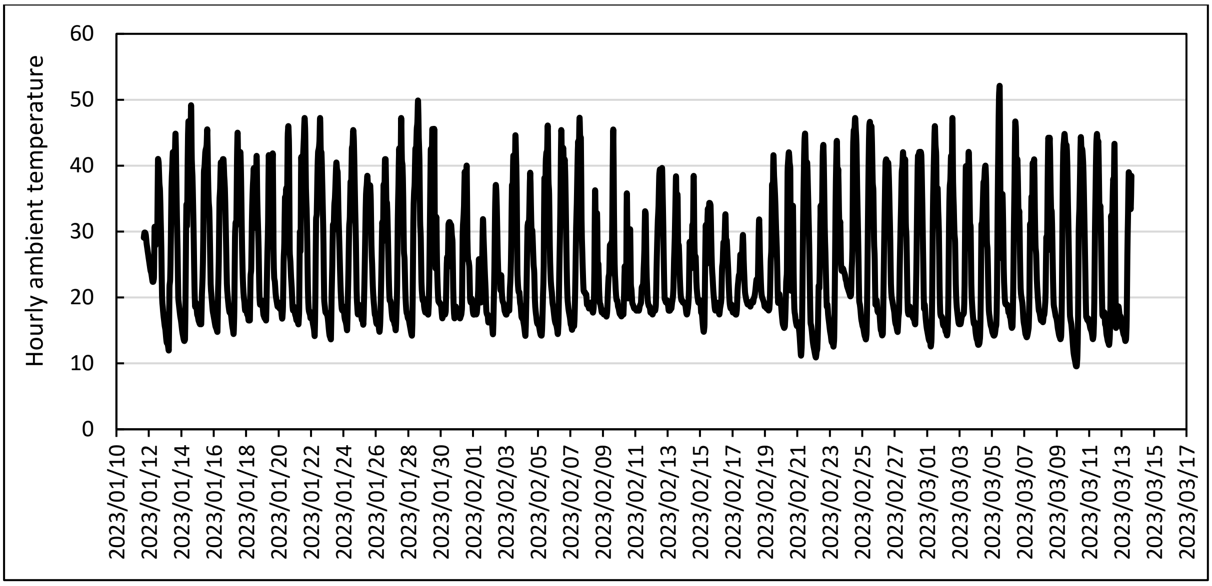

Figure 6.12: Hourly fluctuations of ambient temperature inside the non-temperature-controlled plastic tunnel at Mme Mbatha's site.

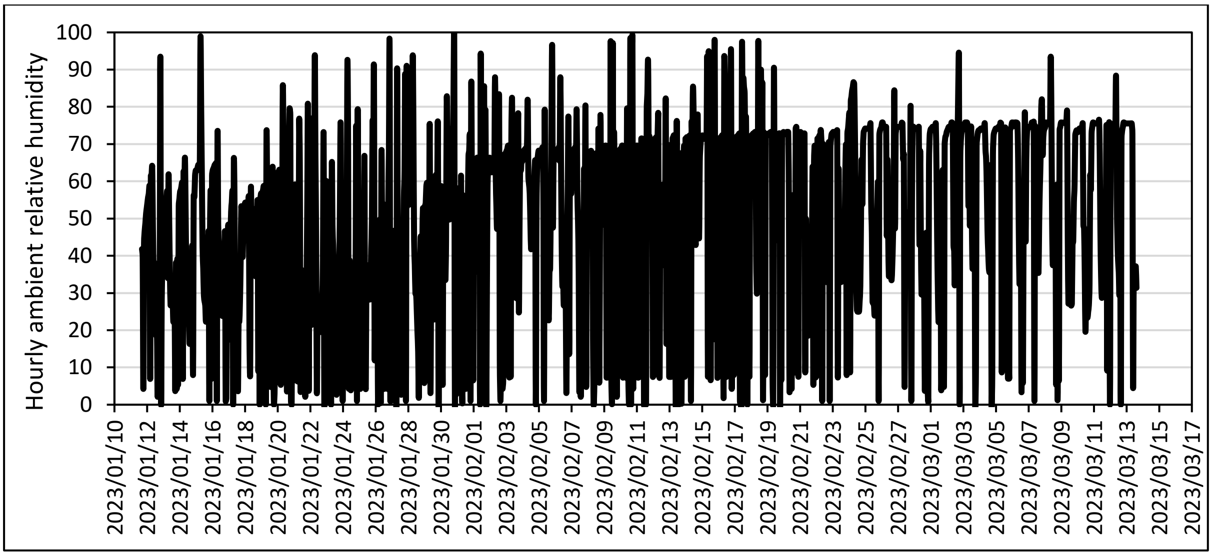

Figure 6.13: Hourly fluctuations of ambient relative humidity inside the non-temperature-controlled plastic tunnel at Mme Mbatha's site.

On a typical hot, humid day, such as the 05th of March 2023 (Figure 6.13), maximum temperatures were reached around midday, while relative humidity fluctuated considerably throughout the day and reached its minimum either at early or late hours of the day. Surprisingly, temperature of the nutrient solution remains steadily stable throughout the day at about 23 and 27 degree Celsius.

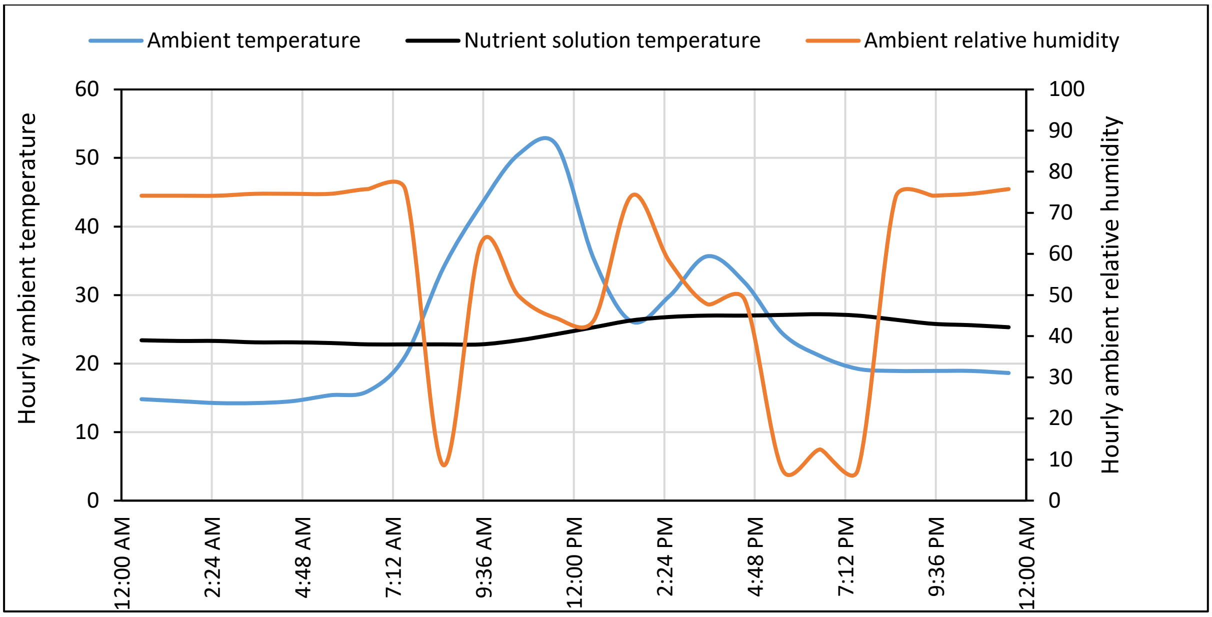

Figure 6.14: Diurnal fluctuations of ambient temperature and relative humidity inside the non-temperature-controlled plastic tunnel, as well as temperature of the nutrient solution at Mme Mbatha's site.

6.*3.1.2 Changes in the nutrient solution EC and temperature levels*

Electrical conductivity (EC) levels of the nutrient solution were typical kept at 1.5 and 3.5 mS/cm. Fertilizers were typically added to the water tank every five days. The pattern and magnitude of hourly temperature of the nutrient solution remained steady constant during the period of measurements. The drop in EC levels indicate a refilling of water in the tank prior to adding fertilizers.

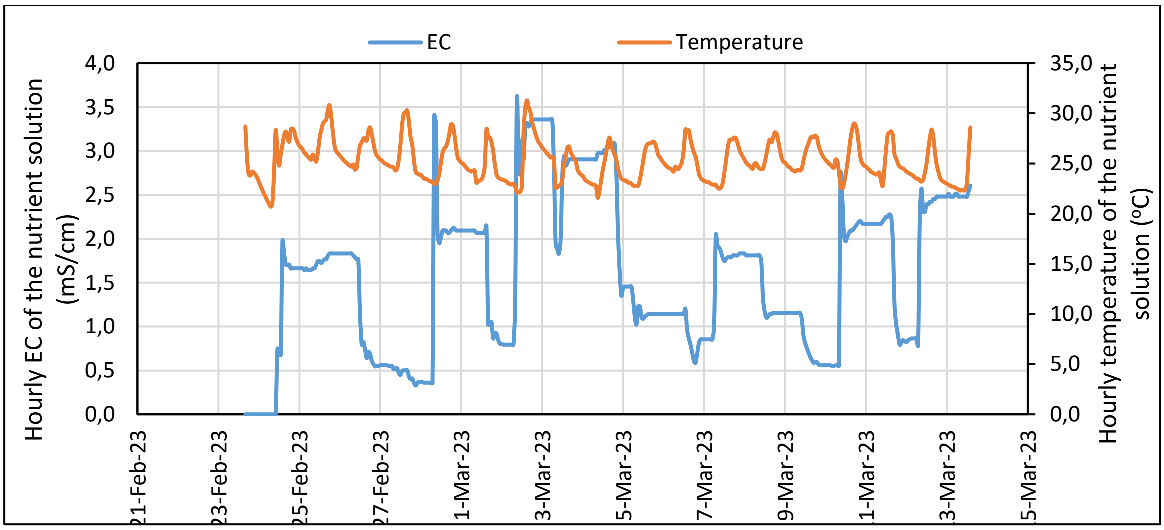

Figure 6.15: Hourly fluctuations of EC and temperature of the nutrient solution in the GFT system at Mme Mbatha's site.

6.3.1.3 Tomato plant morphological and physiological parameters

The two tomato cultivars being evaluated (Trinity and Jumphak) are both commercially certified, indeterminate and adapted to greenhouse hydroponic production systems. Trinity considerably outperformed Jumphak in terms of height, however, both cultivars revealed comparative performance in terms of other morphological and physiological parameters measured.

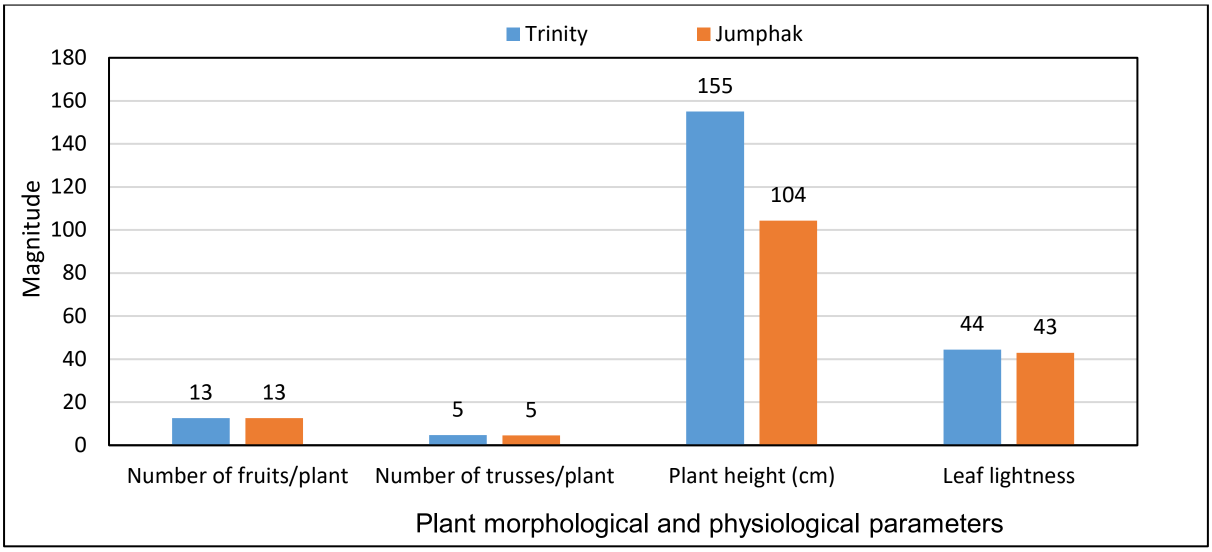

Figure 6.16: Tomato plant morphological and physiological parameters in the GFT system at Mme Mbatha's site.

6.3.1.4 Tomato water and fertilizer usage

In terms of crop water and fertilizer usage, on average, the tomato plant water consumption varied from 0.1 to 1.0 L/day, while fertilizer usage varied from 0.04-0.05 to 0.4-0.5 g/day per plant, from the transplanting period up to eight weeks old. Considering a plant population of 900 plants per tunnel, the water and fertilizer consumption were a maximum of 4500 L and 1.8 kg of each fertilizer per tunnel every five days.

Table 6.2: Tomato water and fertilizer usage

Weeks after transplanting	Water use per plant (L/day)	Fertilizer use per plant (g/day) Hygroponics	Calcium Nitrate	Potassium Nitrate
zero to two weeks	0.1	0.05	0.04	-
two to four weeks	0.3	0.15	0.10	-
four to six weeks	0.6	0.30	0.20	0.10
six to eight weeks	1.0	0.50	0.40	0.15

6.3.2 Nutrient Film Technique – Mme Zodwa's site

6.3.2.1 Environmental variability inside the hydroponic structure

Hourly ambient temperatures inside the non-temperature-controlled plastic tunnel at Mme Zodwa's site fluctuated between 10 (night-time) and 45 degree Celsius (daytime). Hourly ambient relative humidity remained constant at 94%. Relative humidity values above 60% can be detrimental to crop growth.

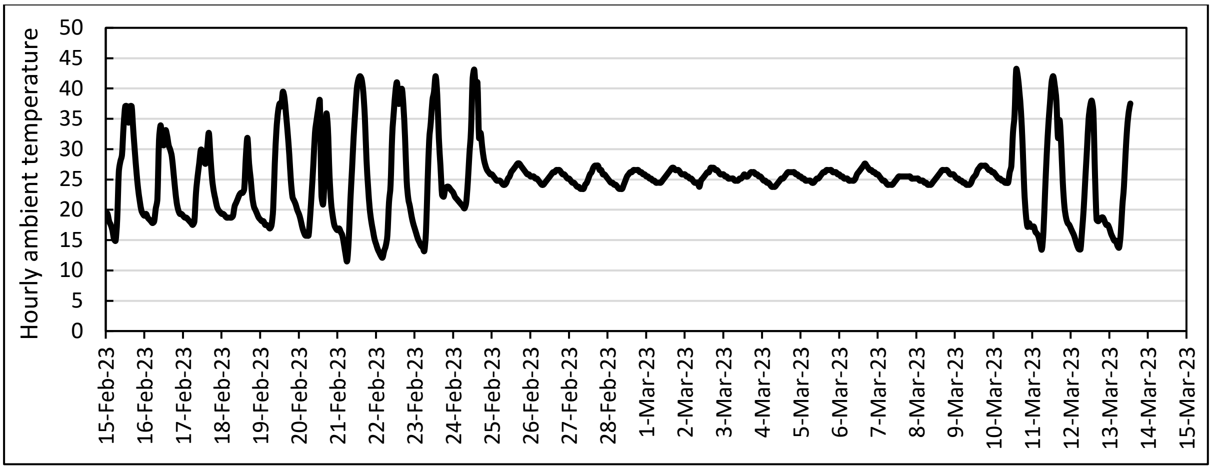

Figure 6.17: Hourly fluctuations of ambient temperature inside the non-temperature-controlled plastic tunnel at Mme Zodwa's site

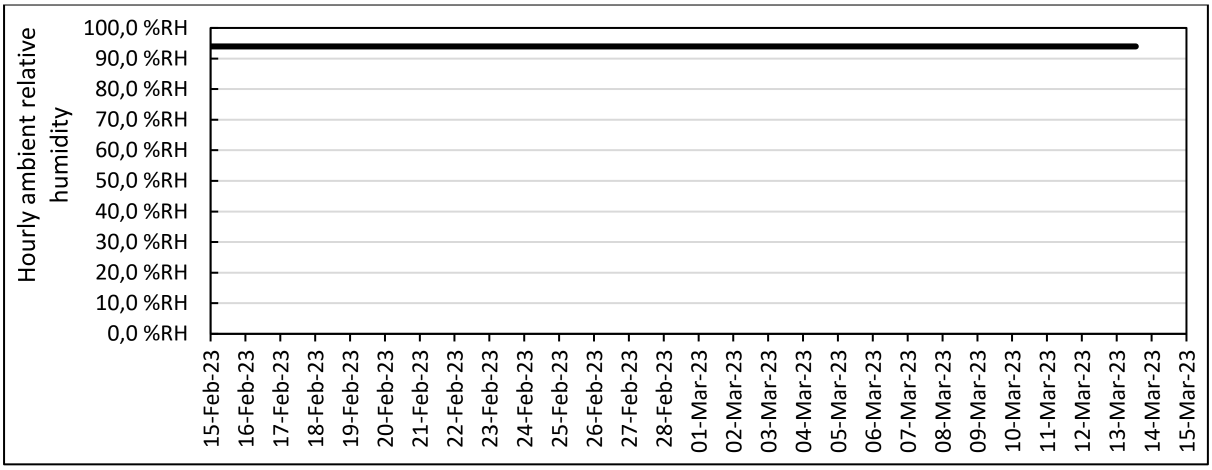

Figure 6.18: Hourly fluctuations of ambient relative humidity inside the non-temperature-controlled plastic tunnel at Mme Zodwa's site.

6.3.2.2 Leafy crops morphological, physiological and yield parameters

A total of 450 seedlings of various types of vegetable (lettuce, Swiss chard) and herb crops (sweet basil) were planted in one A-frame structure at a 10 cm spacing between plants. The best performing crop was green lettuce (Green Oak 'Multired 3'), followed by Sweet basil 'Genovese'. These crops were more tolerant to the effects of regular loadshedding (up to a maximum of four hours during the day).

Table 6.3: Leafy vegetable and herb crops morphological, physiological and yield parameters.

	Average growth, yield and physiological parameters per plant						
Crop	Fresh mass (g)	Number of leaves	Root length (cm)	Canopy diameter (cm)	L	a	b
Red lettuce	33.8	18.4	24.0	16.6	30.3	5.2	3.3
Green lettuce	152.4	27.2	66.8	25.4	41.2	-12.7	25.3
Sweet basil	51.2	42.8	11.2	64.6	44.1	-11.8	15.0
Swiss chard	59.2	27.0	18.0	6.4	40.8	-12.4	16.9

6.3.2.3 Leafy crops water and fertilizer usage

On average, the water consumption of leafy vegetables tested, varied from 10 to 20 ml per day per plant, while fertilizer usage fluctuated from 5-19 to 10-15 mg per plant per day. Scaled-up figures to a tunnel level containing 12 standard A-frames and 10 000 plants, the water and fertilizer estimates would be 2800 l and 2.0 kg of each fertilizer every two weeks.

Table 6.4: Leafy vegetable and herb crops water and fertilizer usage.

Weeks after transplanting	Water use per plant (ml/day)	Fertilizer use per plant (mg/day)	
		Hygroponics	Calcium Nitrate
Weeks 1-2	10.0	10.0	5.0
Weeks 2-4	20.0	15.0	10.0

6.3.3 Hydroponics Planter – Westonaria site

6.3.3.1 Environmental variability inside the hydroponic structure

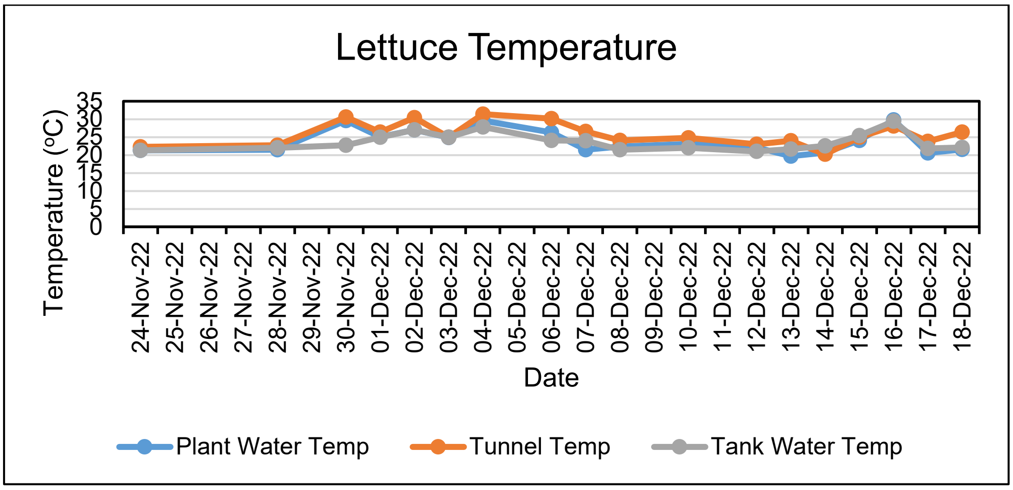

Figure 6.19: Daily fluctuations of temperature within the plant environment, tunnel and nutrient solution at AB Farms's site.

6.3.3.2 Crop yield parameters

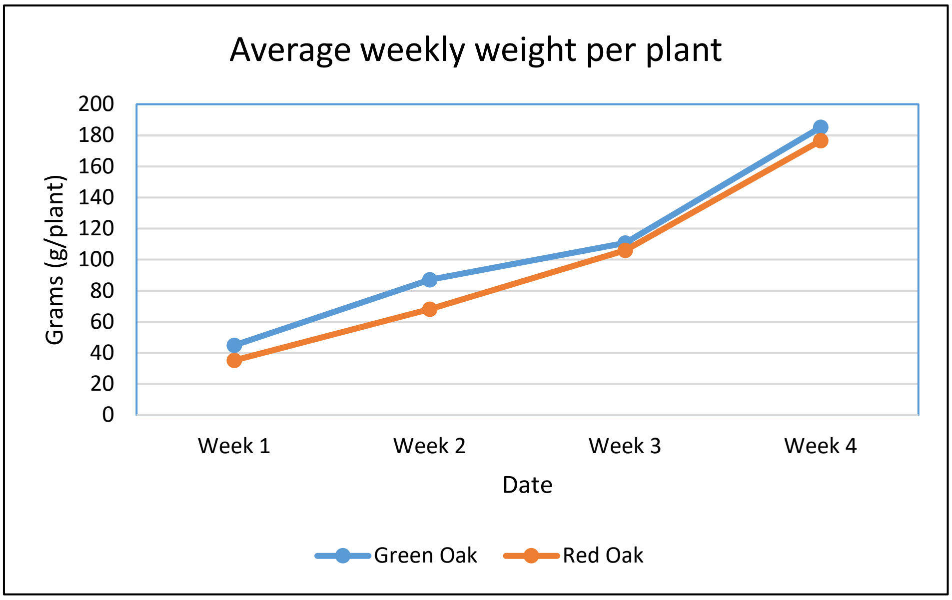

Figure 6.20: Fresh mass of two lettuce varieties at AB Farms's site.

6.3.3.3 Crop water and fertilizer usage

Table 6.5: Lettuce water usage per plant per day.

Crop	Water input(l)	Water remaining(l)	Water utilization(l)	Seedlings(l)	Utilization/plant/day (ml)
Lettuce	9500	1500	8000	3600	70

Table 6.6: Lettuce fertilizer usage per plant per day.

	Fertilizer usage per plant per day		
Crop	Hydroponic mix (mg)	Calcium Nitrate(mg)	Magnesium Sulphate (mg)
Lettuce	50	40	0

6.4 Conclusions and recommendations

This project contributed to development of appropriate crop production practices for a range of vegetable and herb crops grown in recirculating hydroponic systems. Optimum production practices developed on-station were implemented at farmers' sites in the Western region of Gauteng Province. Non-temperature-controlled tunnels at Mme Mbatha and Mme Zodwa sites, as opposed to the temperature-controlled tunnel at AB Farms, resulted in excessively high ambiente temperatures and extreme values of ambient relative humidity. These excessive levels of environmental conditions could be detrimental to plant growth. Nonetheless, crop being investigated at both Mme Mbatha and Mme Zodwa site have demonstrated great performance to date. This is in spite of several challenges experienced under on-farm conditions, including the prevalence of loadshedding, lack of mechanization to conduct regular preventative chemical spraying and knowledge/skills building amongst farmers that are still scarce. Two emerging commercial farmers were introduced innovative recirculating hydroponic systems, which are highly efficient in terms of water, fertilizer and space utilization. Farmers were also trained on pests and diseases control, hydroponics systems management, post-harvest handing and record keeping. For better performance of recirculating hydroponic systems at farmers' sites, there is a need to install solar-operated pumps, establish a more reliable and sustainable water source such as groundwater utilization through boreholes and conduct further training involving local farmers and youth.

For better performance of recirculating hydroponic systems at farmers' sites, there is a need to install solar-operated pumps, establish a more reliable and sustainable water source such as groundwater utilization through boreholes and conduct further training involving local farmers and youth.

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CHAPTER 7: POSTHARVEST TECHNOLOGIES FOR HYDROPONIC FRESH PRODUCE – A CASE STUDY OF LETTUCE

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7.1 Introduction and background

Lettuce (*Lactuca sativa* L.) is the most popular, commercially produced leafy vegetable worldwide (Simko et al., 2014). Lettuce belongs to the family compositae and is one of the vegetables that is widely consumed, and it has a good contribution to human health (Malejane et al., 2017). Lettuce is one of the basic components of salads prepared both in homes and in commercial establishments (Schvambach, 2020). Lettuce contains low-calorie and is a good source of dietary vitamins (A, C, K), folate, fiber, and consuming food high in dietary fiber has a positive effect on the proper functioning of the digestive system (Sularz, 2020).

Lettuce is packaged in several ways such as fresh-cut, lettuce from the base (head lettuce, ice bag), and living lettuce for the market. Fresh-cut lettuce is the primary ingredient in packaged, ready-to-eat salads. Fresh cut lettuce is prevalent in retail markets of South Africa, is essential to meet market demand and consumers need a year-round supply of good quality products. Living lettuce is a growing category to the market having a garden in the fridge. The enormous potential to expand the living lettuce market segment if products meet consumers' needs. A key issue for the success of the living lettuce industry is the consistency and length of shelf-life of the product. Identifying a "best practice" approach to ensure a quality product with a longer shelf life.

Consumers have an increasing interest in safer and healthier food. Nutrition quality and bioactive compounds in the different food sources have been widely studied, focusing on the contribution of phytochemical consumption to human health. Lettuce is mostly consumed raw which makes it a good source of dietary phytochemicals compounds. Consumption of such as phenolic and flavonoid compounds have many health benefits due to their antioxidant properties (Malejane et al., 2017). Lettuce has antioxidant properties resulting from the high level of caffeic acid, flavonols, and carotenoids (Sularz, 2020).

Harvesting, handling and packaging technologies for fresh lettuce have continually evolved as the market has expanded, for the transport and retail of vegetables. Food packaging plays a vital role in preserving food throughout the distribution chain. The development of novel food packaging (active packaging and modified atmosphere) has not only increased the shelf life of foods, but also their safety and quality, therefore bringing convenience to consumers. Directly related, and interlinked, with food packaging is the concept of shelf life – the length of time that foods, pharmaceutical drugs, beverages, chemicals, and perishable products are given before they are considered unsuitable for sale, use, or consumption. Without packaging, the processing of food can become compromised as it is contaminated by direct contact with physical, chemical, and biological contaminants (Wani et al., 2021). The techniques to increase the shelf life and presentation of the product to the consumer, packing vegetables in suitable packages, and storage under refrigeration are also important. Sufficient packaging is one of the main factors to avoid post-harvest losses, mechanical damage. The quality of a food product is a difficult point to define since it varies with its type and its purpose. For the consumer, some appearance characteristics such as size, shape, color, absence of spots, texture, taste, scent, and nutritional value are the main quality attributes required. The maintenance of the vegetables at a great temperature for preservation, from the harvest to the consumption, reduces the respiratory rate as well as the microbiological and enzymatic activity, allowing a better post-harvest life of the vegetable (Rickman et al., 2007).

Discoloration of the cut surfaces of lettuce is a major quality defect for consumers (Turner, 2020). The browning results from wounding and the breaking of cells (Rogers, 2006). Decay of lettuce, seen as darkening, wilting, and deterioration, will eventually still occur in MAP and causes the end of the salad's shelf-life. Decay of salad in MAP is a heritable trait of lettuce conditioned by both small and large effect quantitative. Browning represents a major challenge that limits the quality and shelf life of packaged lettuce. The lack of effective browning control has resulted in processors relying on modified atmosphere packaging (MAP) to achieve low oxygen atmospheric conditions and maintain the shelf life (Teng, 2019).

The important sites that undergo greatly from postharvest losses, some estimates from the farmer's field, processing, cleaning and cutting (15-20%), packaging, transportation (30-40%), and marketing (30-40%). Horticultural crops provide nutritional and healthy foods to human beings, but also generate a considerable cash income for growers. Horticultural crops normally have high moisture content, high perishability, and tender texture. Poor handling of high-value nutritious products can deteriorate and rot in a matter of hours or days (Sem, 2020). Sustainable agriculture, especially in developing countries can improve, farm income, food security, and poverty alleviation. The fruit and vegetable sector suggests that about 30-40% of fruit and vegetables are lost or abandoned after leaving the farm gate. Huge postharvest losses result in diminished returns for producers (Xavier, 2018). The postharvest management of fruit and vegetables in most developing countries in the region is far from satisfactory. The major constraints include inefficient handling, processing, packaging, transportation, poor technologies for storage, and involvement of too many diverse actors; and poor infrastructure (Rolle, 2005; Xavier, 2018). The color, size, texture, and taste are important parameters for the successful marketing of lettuce and these factors determine the market price and consumer preference.

The hydroponic cultivation of lettuce can offer producers greater economic profitability, fast financial return due to sanitary and nutritional quality (Xavier, 2018). Hydroponic cultivation is related to the high initial cost of production, construction of greenhouses, tables, benches, hydraulic and electric systems. The hydroponic cultivation of lettuce has economic viability when the crop is grown with mineral solutions, but there is no formulation considered ideal since it involves many variables and their interactions (Filho et al., 2018). There is a lack of information on the economic viability of the cultivation of vegetables. The analysis of the economic viability of leafy lettuce hydroponic cultivation using mineral solutions is important (Filho et al., 2018). The cultivation of lettuce in hydroponic systems is already widely spread, and it has a short life cycle (Xavier, 2018). Vertical farming uses very less water at least ten times lower than conventional farming. Overall, vertical farming restores the urban ecosystem where traditional agriculture has been encroaching upon the natural ecosystem. The most crucial factor of vertical farming is its economic viability. Vertical farming can be in urban areas, it would be possible to sell products directly to the consumers reducing transportation costs, which can constitute up to 60% of the total cost. Vertical farming also intensifies crop production and enhance total yield, reduces the production time, and uses fewer production inputs, such as water and fertilizers (Islam, 2021).

7.1.1 Problem statement

Leafy lettuces are highly perishable due to their higher water content, active and faster biological and physiological reactions, and easily bruised after harvest. Despite its popularity and nutritional facts, consumers may reject or cancel buying decision to buy leaf lettuce when it loses quality or freshness besides their concern about the safety of the produces when the commodities are consumed as fresh. Preserving the freshness and quality characteristics of leaf lettuce are the main challenges for growers and suppliers to maintain the continued supply of this delicate produce to the consumers. Leafy lettuce has poor storage potential after harvesting due to high respiration. Despite the great consumption, the leafy vegetables in general present high fragility and may deteriorate in a few days after the harvest. However, immediate consumption or use of post-harvest conservation techniques is necessary (Schvambach, 2020). There is limited information on packaging material and shelf life of leafy lettuce produced in hydroponic system.

7.1.2 Aim and Objectives

- The study aims to preserve leafy lettuce to lower postharvest losses in the retail market.

The following objectives were formulated:

- To assess packaging material and packaging technique to increase the shelf life of lettuce;
- To determine the quality and quantity of living lettuce in different packaging techniques.

7.2 Research methodology

7.2.1 Description of the study site

The experiment will be conducted at the Agricultural Research Council (ARC) – Vegetable and Ornamental Plants, Roodeplaat, Pretoria, South Africa during the summer and winter season 2021. Lettuce was harvested in a hydroponic system, A frame structure. During harvesting eight plants from each plot were collected for the determination of postharvest storage of leafy lettuce.

7.2.2 Trial layout

The trial consisted of a factorial arrangement of different post-harvest packaging types (Figure 7.1 shows living lettuce packaging type) versus pre-harvest spacing levels laid out in a randomized block design with three replications in a cold-room set at 5 degrees Celsius at ARC-VIMP (Figure 7.2).

Figure 7.1: Living lettuce packed in a crate ready to be taken to the cold room at ARC-VIMP
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REP 1									
10 cm living lettuce control 1	20 cm loose lettuce	10 cm whole plant paper wrapped root	10 cm loose lettuce control 2	20 cm living lettuce	10 cm living lettuce plastic wrapped root	20 cm whole plant paper wrapped root	10 cm living lettuce paper wrapped root	20 cm living lettuce paper wrapped root	20 cm living lettuce plastic wrapped root
REP 2									
20 cm whole plant paper wrapped root	10 cm loose lettuce control 2	20 cm living lettuce	20 cm loose lettuce	10 cm living lettuce control 1	20 cm living lettuce plastic wrapped root	20 cm living lettuce paper wrapped root	10 cm living lettuce paper wrapped root	10 cm whole plant paper wrapped root	10 cm living lettuce plastic wrapped root
REP 3									
10 cm living lettuce plastic wrapped root	20 cm living lettuce	20 cm living lettuce plastic wrapped root	20 cm living lettuce paper wrapped root	20 cm whole plant paper wrapped root	10 cm whole plant paper wrapped root	10 cm living lettuce paper wrapped root	10 cm loose lettuce control 2	20 cm loose lettuce	10 cm living lettuce control 1

Figure 7.2: Post-harvest trial layout at ARC-VIMP.

7.2.3 Packaging types

Leaves (50 g) of leafy lettuce were packaged separately in bioriented polypropylene packages obtained from Packaging World (Pty) Ltd., Durban, South Africa. Bag (a) BOPP bag: The thickness of the bags was 35 µm (size 240 cm x 280 cm ANTI FOG bag), and sealed with a heat sealer in order to create a suitable internal atmospheres. Bag (b) 25 mm X 25 zip lock bags, and Bag (c) paper wrap or roller towel used for live lettuce (Figure 106).

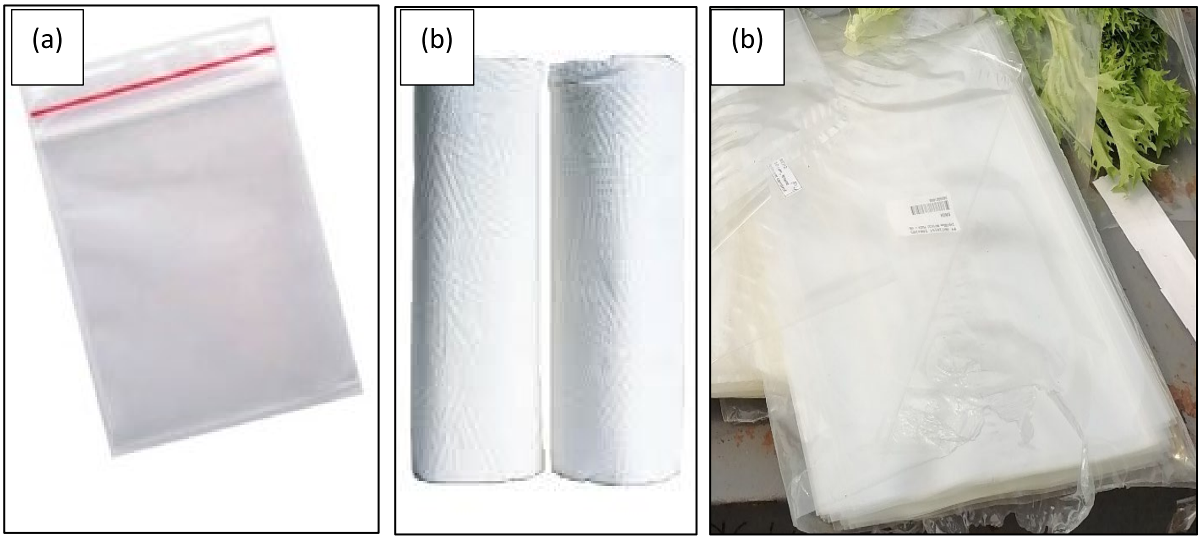

Figure 7.3: Zip Lock bags(a), paper towel (b) and BOP Anti Fog bag(c).

7.2.4 Research treatments

The following research treatments were tested during the experimental period:

- 10 cm Whole plant living lettuce paper wrapped root;
- (2) 10 cm Living lettuce paper wrapped root;
- (3) 10 living lettuce plastic wrapped root;
- (4) 10 living lettuce control;
- (5) 10 Loose lettuce control;
- (6) 20 cm Whole plant living lettuce paper wrapped root;
- (7) 20 cm Living lettuce plastic wrapped root;
- (8) 20 living lettuce plastic wrapped root;
- (9) 20 living lettuce control, and
- (10) 20 Loose lettuce control. 20 ml water in the packaging material.

7.2.5 Storage environment

A Multiplex Cold room was used for the study, set at about 5 ˚C in temperature (Figure 7.4). The temperature data was collected with the Data logger. The samples were packed in crates, 6 samples per crate, and stored on shelves (divided into three – top, middle and bottom shelves), following in a randomized complete block design.

Figure 7.4: A Multiplex Cold room was used to study the shelf life of leafy lettuce grown in a vertical nutrient film hydroponic system at ARC-VIMP.

7.2.6 Physical parameters for data collection

The following physical parameters were collected:

- (1) Packaging type;
- (2) Storage period;
- (3) Percentage weight loss;
- (4) Leaf colour parameters L, a, b
- (5) Wilting
- (6) Decay
- (7) Yellowing
- (8) Browning
- (9) Shelf life of fresh produce after 3, 6 and 9 days of post-harvest.

The lettuce leaves were stored in a cool room for 9 days, and the data was collected every 3 days. The Sampling number consisted of six plants per treatment per replication. The cold room temperature was selected according to the retail conditions (Spar Roodeplaat (0-7˚C), and Derdepoort (0-2˚C), Shoprite (0-6˚C), Ok (0-8˚C), Checkers (0-8˚C) shops. The evaluation of color on the leaf surface was measured with a chromameter (CR-400 Chroma Meter, Konica Minolta Inc., Tokyo, Japan) using the colorimetric coordinates of lightness (L*), hue (h◦), and chroma (C*) (McGuire et al., 1992).

7.3 Results and discussion

The average, maximum and minimum ambient temperature and relative humidity during the experimental period are presented in (Table 7.1).

Table 7.1: Cold-room temperature recorded during the trial.

	Temperature (°C)	Relative Humidity (%)
Maximum	4.31	99.95
Average	3.57	83.60
Minimum	2.82	67.24

7.3.1 Moisture content and wilting

The percentage of relative moisture loss of lettuce under different post-harvest packaging types and two pre-harvest spacing treatments during storage are presented in Figures 108 and 109 respectively. A substantial amount of moistures losses was recorded on the whole plant living lettuce paper wrapped root, living lettuce paper wrapped root, living and lettuce plastic wrapped root on both 10 cm and 20 cm pre-harvest spacing. Control sample, on the other hand, showed intermediate water loss trend in between the amount of moisture loss from day zero throughout the storage period. Loose lettuce control and living lettuce control showed higher moisture retention in the stored samples. This result clearly indicated the beneficial effect of using packaging film in maintaining moisture content of lettuce during long term storage. At the end of the storage, we recorded less than 5% of moisture loss in loose lettuce control and the minimum of less than 7% on living lettuce control treatments, respectively, whereas these losses on uncontrol treatment were 20% in average. Loose lettuce control particularly had the lowest wilting percentage, especially when the plants were spaced at 10 cm (Figures 7.7 and 7.8). The reason for minimum moisture losses found on wrapped treatment could be attributed to high water vapor permeability. In agreement with the current fundings, Rizzo and Muratore (2009) also found less than 3% total moisture loss after

31 days. Many researchers have demonstrated that packaging can protect water loss and can maintain the quality of perishable commodities (Lee et al., 2007; Lee, 2008; Lee et al., 2008). Moisture content in food can have a significant impact on product's quality and shelf life (Li et al., 2017).

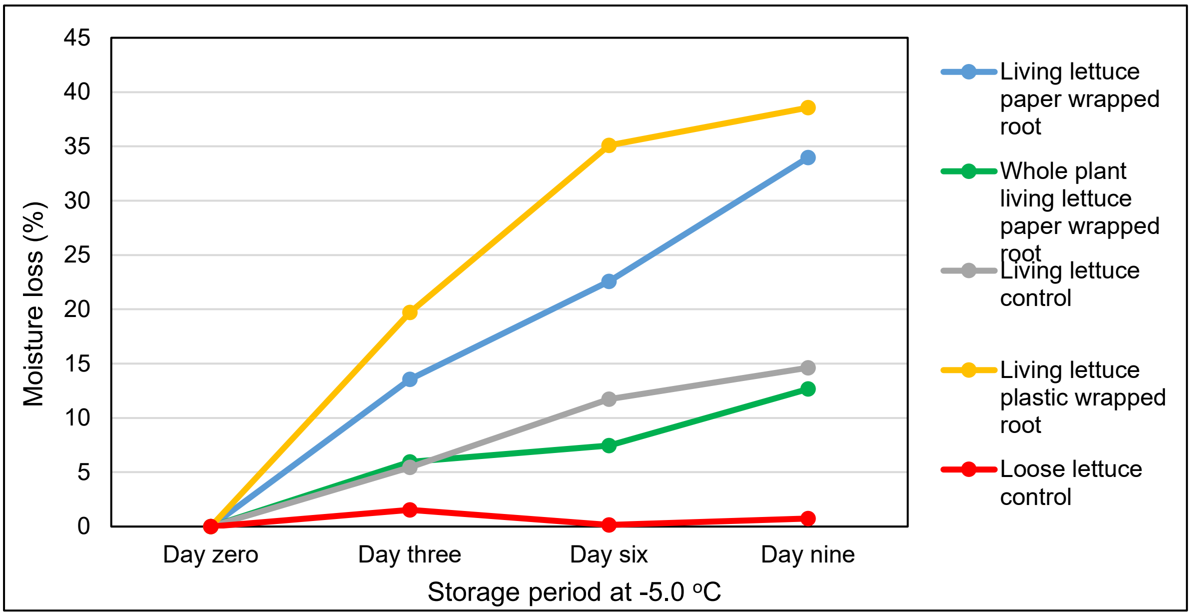

Figure 7.5: Leafy lettuce post-harvest moisture loss using 10 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

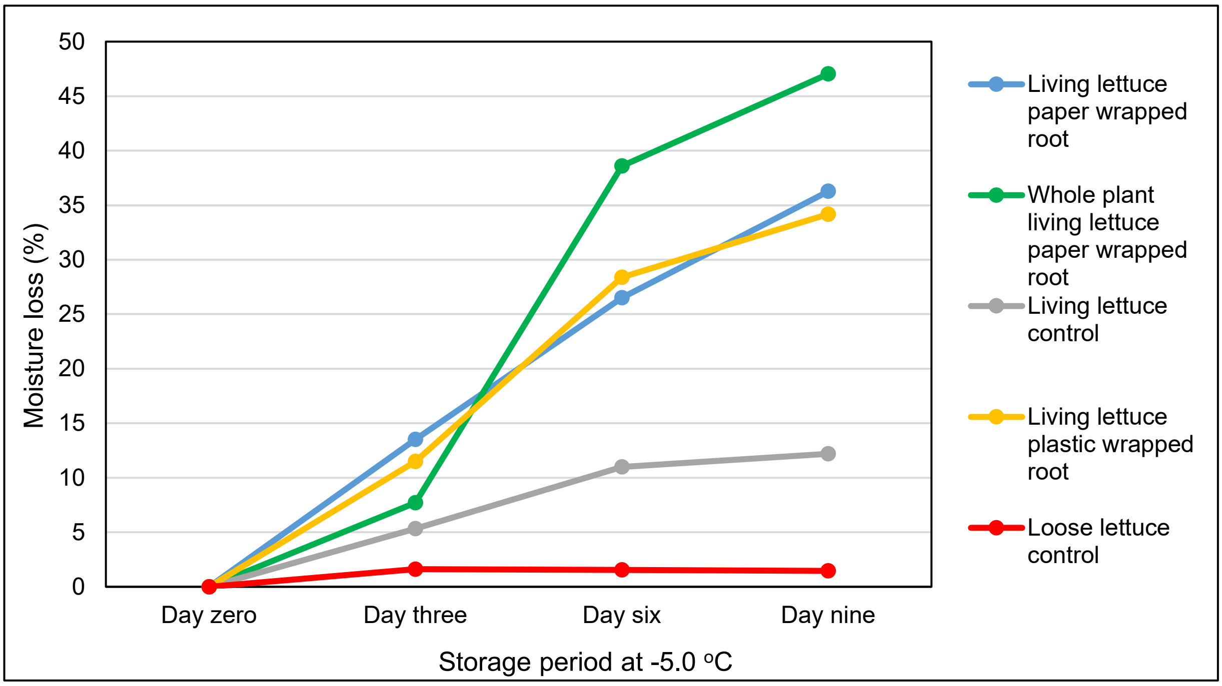

Figure 7.6: Leafy lettuce post-harvest moisture loss using 20 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

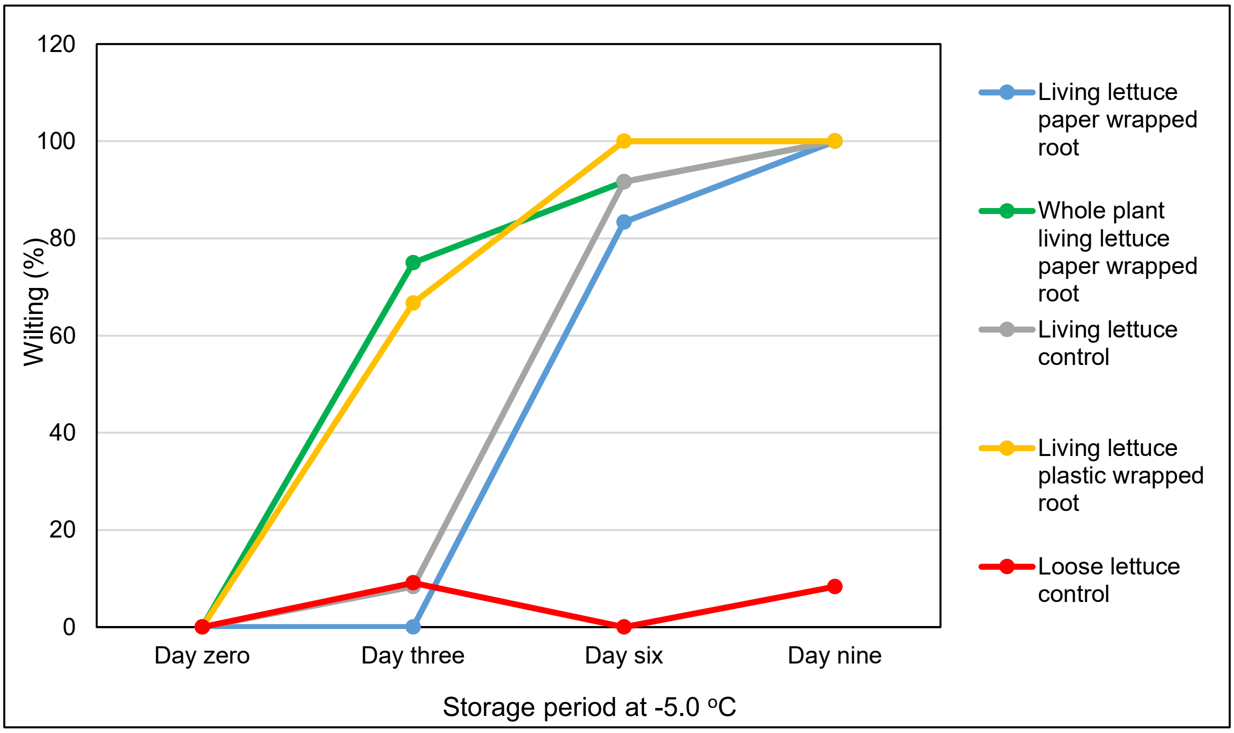

Figure 7.7: Leafy lettuce post-harvest wilting using 10 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

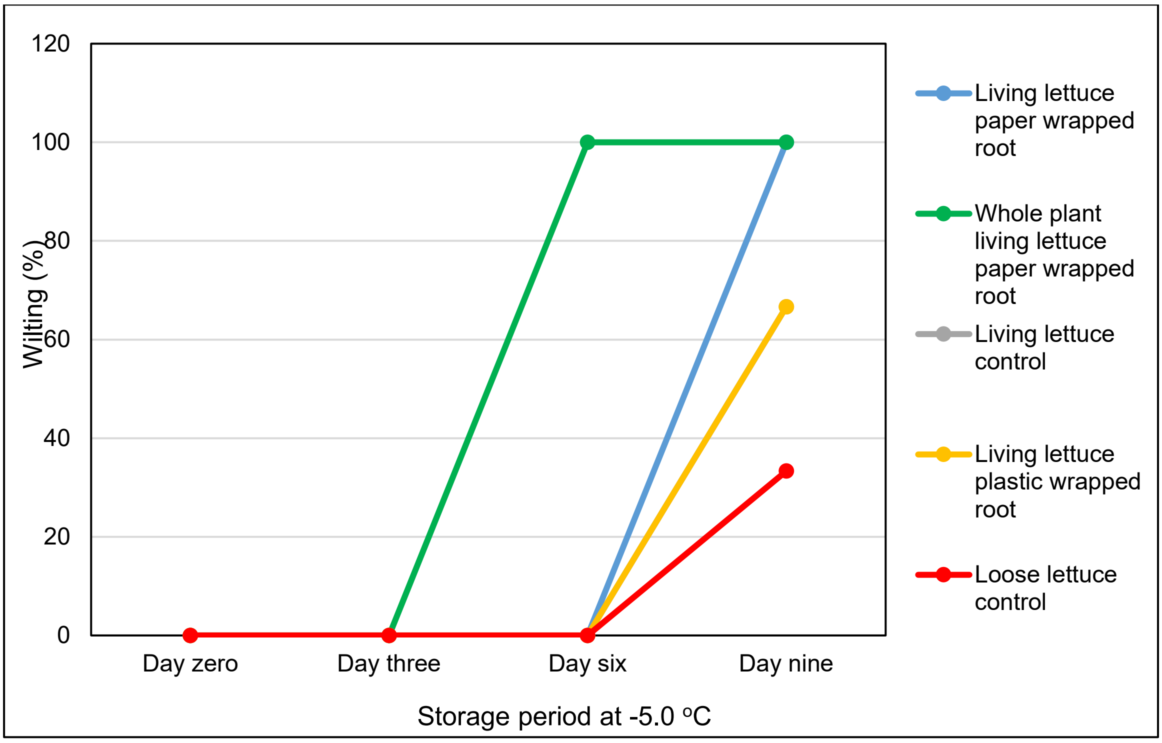

Figure 7.8: Leafy lettuce post-harvest wilting using 20 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

7.3.2 Decaying

Figures 7.9 and 7.10 show that the experimental plants in all treatments had slight sighs of decaying throughout the storage period. Most of the decay was observed within the first three days of the experimental trial. However, both figures show that there was a substantial reduction in decay during storage. Packaging and temperature might have reduced exposure to microorganisms and contaminants. Similar findings have been made with bell peppers stored in perforated packaging which had a lower decay incidence (Yehoshua et al., 1998). There was no decay recorded on the 20 cm living lettuce paper wrapped root and 20 cm living lettuce control. Whereas, on the loose lettuce control the decaying was less than 1% throughout the storage period.

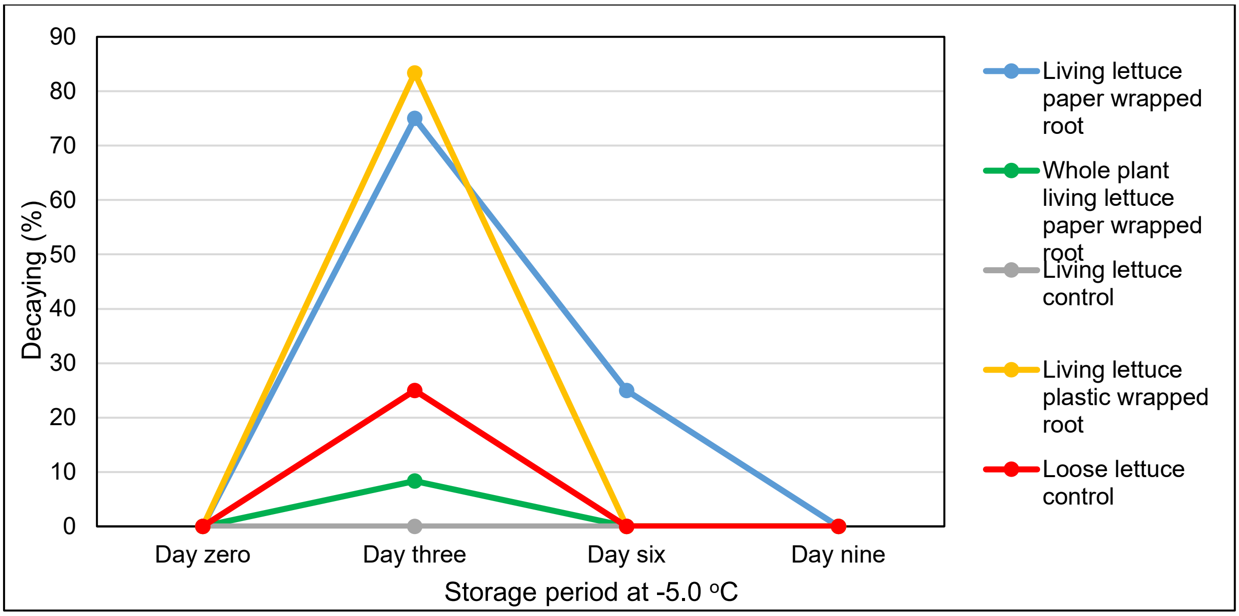

Figure 7.9: Leafy lettuce post-harvest decaying using 10 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

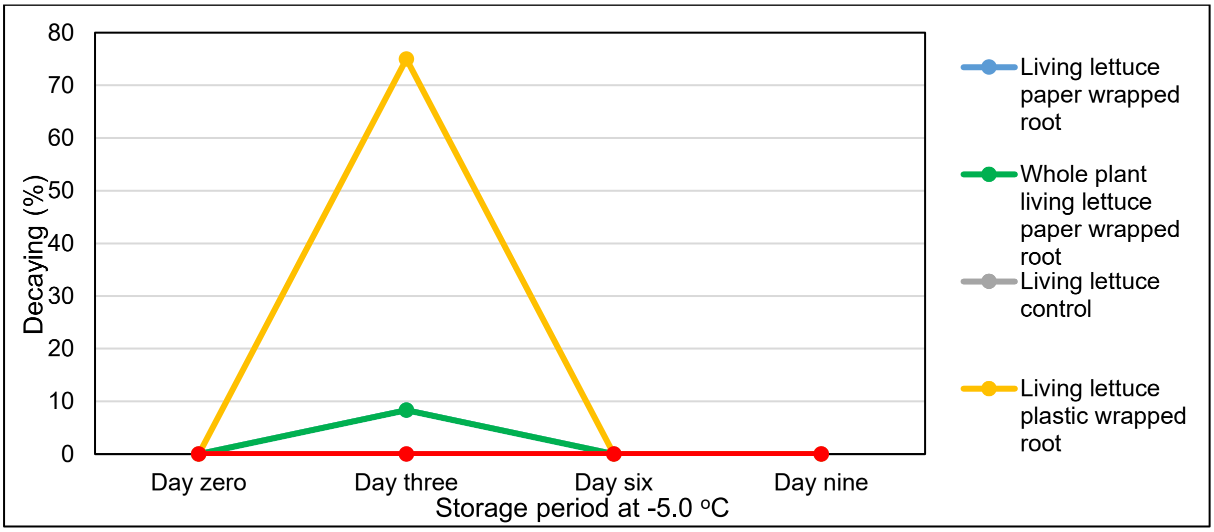

Figure 7.10: Leafy lettuce post-harvest decaying using 20 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

7.3.3 Yellowing

Loose lettuce packaging treatment outperformed all the treatments in terms if yellowing, which most likely result of being the least affected in terms of moisture loss, wilting and decay

(Figures 7.11 and 7.12). Spacing the plants at 20 cm at pre-harvest phase completely eliminated yellowing in loose lettuce control.

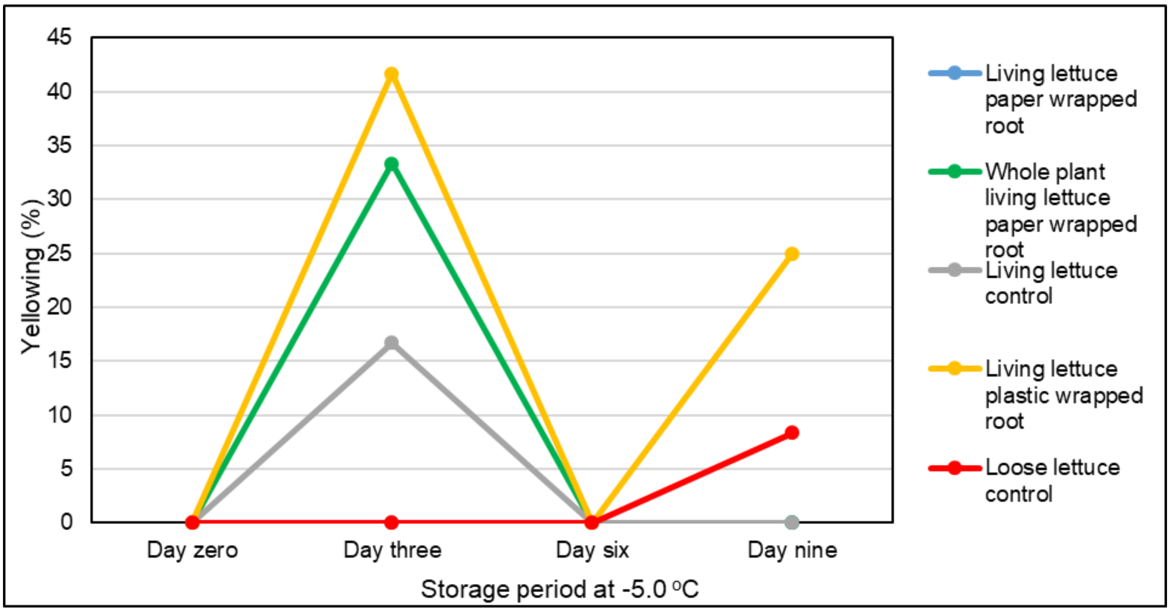

Figure 7.11: Leafy lettuce post-harvest yellowing using 10 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

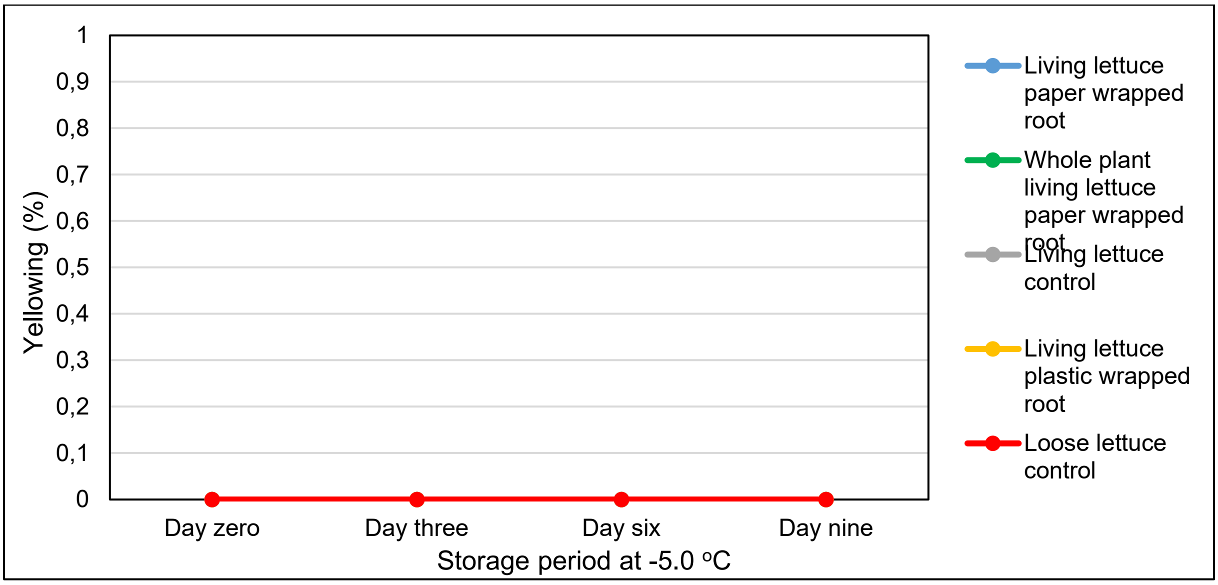

Figure 7.12: Leafy lettuce post-harvest yellowing using 20 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

7.3.4 Browning

Browning is well known to play a significant role in the deterioration of fresh lettuce quality. Several studies have found that browning can vary between lettuce types and high CO_2 environments, which is beneficial for browning control (López-Gálvez et al., 1996). For fresh harvested lettuce, browning is a critical parameter for identifying it as incompatible with consumers (Watkins, 2000). In the present study, (Figures 7.13 and 7.14) show that browning was recorded on 10 cm from day zero and increased during storage and until the end of the experiments. It is also evident that there was a gradual increase of browning 9 days of storage and visual quality of lettuce deteriorated more repeatedly from day three today six. However, there was a slight. On the other hand, 10 cm living lettuce plastic wrapped root and whole plant living lettuce paper wrapped showed slight delay of browning from day three to today six. On the other hand, living lettuce paper wrapped root exhibited a better overall visual quality from day zero to day six compared to other treatments during storage. However, after day six it was noted that the living lettuce paper wrapped root point a hedonic scale, representing above the limit of stability, which was considered different from the others.

One of the most important quality deterioration during postharvest, transport and storage period is the loss of green colour (i.e. leaf browning). The degree of browning increased significantly on loose lettuce control during storage. Similar results were also recorded for romaine lettuce (Lee, 2008). It is also noted that the degree of browning was significantly less on 20 cm sample from day zero to day six on living lettuce paper wrapped root, whole plant living lettuce paper wrapped, living lettuce control and living lettuce plastic wrapped root compared to 10 cm samples. However, living lettuce control retained overall visual quality throughout the storage period.

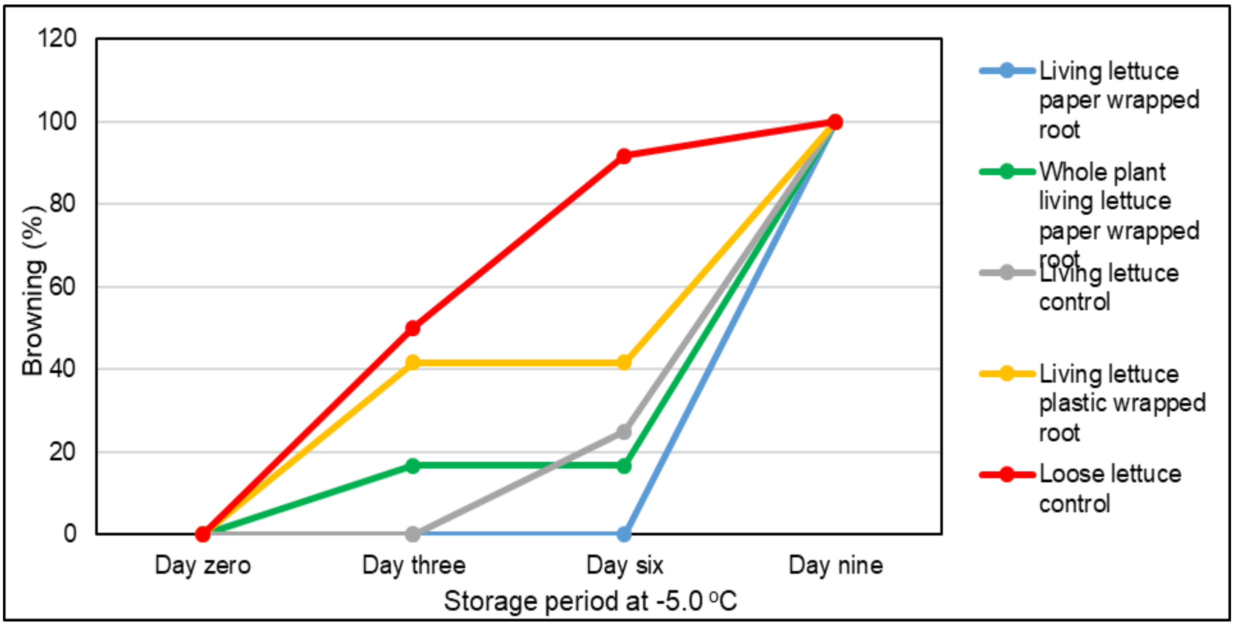

Figure 7.13: Leafy lettuce post-harvest browning using 10 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

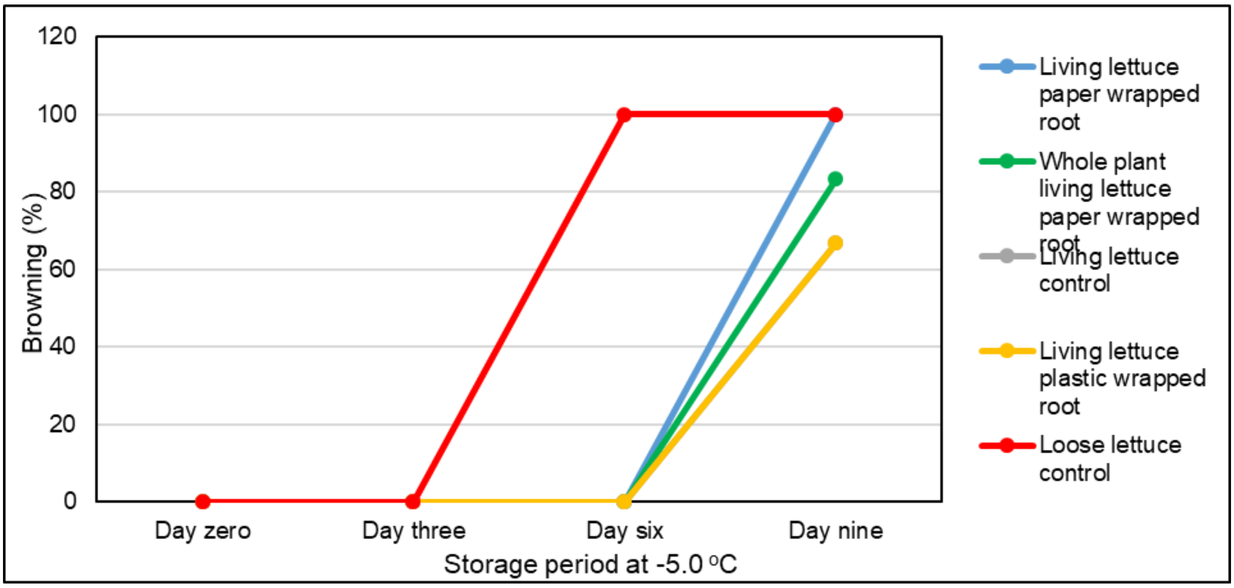

Figure 7.14: Leafy lettuce post-harvest browning using 20 cm plant spacing in a vertical recirculating hydroponic system at ARC-VIMP.

7.3.5 Leaf colour

Table 7.2 shows changes in color parameters L*, a*, and b* which define the quality of lettuce leaves. During storage, all samples showed a gradual decline in overall color quality (with values of colour parameters increasing from day zero to day three), with loose lettuce control showing the highest rate of decline. The decline in L*, a*, and b* for all treatments was less than 11% of their initial value at the end of storage period (9 days). Quality decline in green or nearly green vegetables, such as green or red leaf lettuce, is a common occurrence because a higher L value indicates an increase in leaf yellowing, which is associated with chlorophyll degradation (Toivonen and Brummell, 2008; Mampholo et al., 2013). Increases in color differences were observed in all samples beginning on the third day of storage, with the lowest in living lettuce control samples and the highest in living lettuce plastic wrapped root (Table 7.2). However, there was no noticeable difference in L*, a*, and b* for all samples after six days of storage, except for the loose lettuce control (Table 7.2). The whole plant living paper wrapped root had the lowest L*, a*, and b* values at the end of storage of the five samples that were stored for up to nine days, followed by the living lettuce plastic wrapped root. The results of our color parameters agreed with those of Manolopoulou and Varzakas (2016) in lettuce, where they described hue angle as an indication of degreasing associated with aging. The higher the increase in L*, a*, and b* values value along with increased values of color difference, indicate degradation in color quality of fresh green vegetables. The lower increase in L*, a*, and b* whole plant living paper wrapped root and living lettuce plastic wrapped root packaging leaf lettuce, as well as the lower increase in L*, a*, and b* whole plant living paper wrapped root and living lettuce plastic wrapped root packaging leaf lettuce, suggest that this packaging leaf lettuce has commercial marketing potential. Color is one of the most important factors influencing consumer food selection. (Table 7.2) shows that color preferences did not change much during storage, except for the last few days. Packaging material has been shown to reduce the activity of color-changing enzymes such as polyphenol oxidase (Yu et al., 2017).

The results of this study revealed that packaging and storage time are important factors to consider when determining the shelf-life stability of loose lettuce. On living lattice paper wrapped lettuce, the shelf life was found to be longer than in loose lettuce. The shelf life of samples of living lattice paper wrapped lettuce was found to be longer than that of loose lettuce, which could be explained by the paper wrap higher oxygen transmission rate.

Table 7.2: Post-harvest leaf lettuce colour parameters as influenced by plant spacing and storage time.

Leaf colour parameter	L		a		b	
Pre-harvest plant spacing	10 cm	20 cm	10 cm	20 cm	10 cm	20 cm
Storage time	Day zero					
living lettuce paper wrapped roots	47.99583	45.8675	-9.41417	-10.1183	15.30333	17.25667
whole plant living paper wrapped root	45.84917	48.26583	-10.9958	-12.7675	17.44	20.87
living lettuce control	42.5575	45.57667	-8.95083	-9.91583	14.41833	16.33083
loose lettuce control	50.445	43.67667	-7.36583	-5.6825	10.30917	9.591667
living lettuce plastic wrapped root	54.40375	46.52667	-11.1281	-9.78333	18.63042	18.035
Storage time	Day three					
living lettuce paper wrapped roots	54.94417	59.38417	-12.9308	-15.44	22.68167	28.77833
whole plant living paper wrapped root	53.16917	59.54417	-12.9658	-15.6367	24.5575	28.43
living lettuce control	56.86167	56.065	-15.7117	-13.6708	25.64167	25.7225
loose lettuce control	62.6025	62.4475	-10.4117	-118.953	19.3825	12.82833
living lettuce plastic wrapped root	56.19854	63.45417	-13.4792	-16.305	23.3425	31.14833
Storage time	Day six					
living lettuce paper wrapped roots	50.85917	54.66583	-14.01	-14.6275	20.04583	23.57667
whole plant living paper wrapped root	51.01583	50.98417	-13.6567	-14.0358	20.47917	24.02417
living lettuce control	50.1525	50.98167	-13.705	-14.0358	20.76583	24.02083
loose lettuce control	52.65917	50.16417	-10.5008	-11.9108	15.44667	18.47917
living lettuce plastic wrapped root	48.64792	54.50667	-13.5704	-14.2725	20.20313	23.21833
Storage time	Day nine					
living lettuce paper wrapped roots	46.4025	42.14583	-11.8692	-13.5975	18.34917	18.1875
whole plant living paper wrapped root	45.0625	51.5925	-13.1058	-12.2275	20.84	23.8425
living lettuce control	46.14333	49.24167	-13.7892	-12.7183	22.22083	25.50167
loose lettuce control	55.6875	56.85083	-92.6192	-11.7667	17.4325	18.83333
living lettuce plastic wrapped root	45.92208	54.05583	-12.2296	-14.8475	19.78083	34.48333

7.4 Conclusions and recommendations

Packaging leaf lettuce in living lattice paper wrap around the roots helped to maintain quality parameters while also extending shelf-life. This was particularly evident under 20 cm plant spacing at pre-harvest phase. Although both whole plant living paper wrapped root and living lettuce plastic wrapped root were able to retain the overall lettuce quality, living lattice paper wrapped had more beneficial effects on shelf life parameters. The findings of this study support the superiority of living lattice paper wrapped packaging material over the other four treatments tested by minimizing wilting, yellowing, decay, browning and changes in color difference values. A cost-benefit analysis is recommended to make more informed decisions about the feasibility of each post-harvest technology.

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CHAPTER 8: ECONOMIC FEASIBILITY OF HYDROPONIC FRESH PRODUCE SALES FOR SELECTED COMMODITIES

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8.1 Introduction and background

The role of smallholder and emerging commercial agriculture is called upon to help feed the estimated 9 billion people in the world by 2050 (Pienaar and Traub, 2015). However, these groups of farmers in South Africa are faced with the challenge of producing high crop yield combined with good quality in order to satisfy the local demand. Very often this demand is not met, mainly due to poor soil fertility, inadequate plant nutrition and adverse climatic conditions (Loeper et al*.,* 2016). Agricultural science has significantly evolved in the last years (Ali et al*.,* 2017). Innovative greenhouse systems such as hydroponics and aquaponics that improve both efficiency and effectiveness are being used in the cultivation of crops (Ali et al*.,* 2017). The advantages for this system include high crop quality, high crop yield, more efficient use of water, reduction in the environmental pollution and a greater control and efficiency in the productive process (Lazo and Gonzabay, 2020). Furthermore, hydroponics highly saves on labour cost as it eliminates the traditional practices that are labour intensive (Mugambi, 2020).

Available, but limited results from the commercial subsector seem to suggest mixed results depending on individual farmers. Miller et al. (2017) highlighted that, investment in greenhouse for hydroponic commercial lettuce and tomato is economically and financially sound, with very promising economic returns on investment. Additionally, Malik et al. (2018) revealed that, hydroponics is economic viable based on high net revenues, gross margins and benefit cost ratios (Malik et al*.,* 2018). Lastly, Abdelmawgoud et al. (2021) reported high returns on investment and viability of hydroponics production system for high-value crops for the commercial farming subsector. In contrary, other studies caution viability of hydroponics (Uddin and Dhar, 2018) further calling for more robust analysis across different high-value crops (Miller et al*.,* 2017). According to Ntinas et al. (2019) hydroponic systems are not sustainable and most of them are not profitable. These controversial findings therefore limit an understanding of associated costs and benefits of hydroponics especially for the smallholder and emerging commercial subsectors (Malik et al*.,* 2018; Morifi et al*.,* 2018). As a result, this study evaluates the costs and benefits of producing in vertical recirculating hydroponic systems, taking lettuce as an exemplary case study.

8.1.1 Problem statement

Hydroponic systems are one of the innovative agricultural methods that do not need soil to carry out agricultural processes (Wagh et al., 2019; Howard et al., 2020). This system depends on fertilizers and water completely to provide the nutritional needs of plants which are necessary for its growth (Abdelmawgoud et al., 2021). Hydroponics highly saves on labour cost as it eliminates the traditional practices that are labour intensive (Mugambi, 2020). However, hydroponic systems are capital intensive (Malik et al., 2018) requiring huge initial injection capital and high maintenance compared to conventional systems which are labour intensive (Lazo and Gonzabay, 2020).

Against this background hydroponics systems have become popular with high value horticultural crops like tomatoes, lettuce and cucumbers (Sharma et al., 2018) especially among the commercial subsectors. Cost benefit analysis studies among the smallholder subsector are very limited and the available few are inconsistent. Some studies suggest high viability of hydroponics among smallholder horticulture farmers (Abdelmawgoud et al., 2021; Malik et al., 2018). To the contrary, some studies suggest non viability of hydroponics among smallholder horticulture farmers because they are not sustainable and most of them are not profitable (Miller et al., 2017; Malik et al., 2018; Morifi et al., 2018). Further studies are therefore required to understand the potential of hydroponics under the smallholder and emerging commercial horticulture subsectors given the claimed advantages of the system.

8.1.2 Study aim and objectives

To evaluate the economic feasibility of varying production practices on the productivity of hydroponically grown vegetable crops in Gauteng Province, South Africa, using lettuce as an exemplary case study.

The following objectives were formulated:

- To investigate fixed and variable input costs of lettuce grown in a vertical NFT system under shadenet and plastic tunnel hydroponic structures;
- To evaluate the economic feasibility of the selected production practices.

8.2 Research methodology

8.2.1 Description of the research trial

An experiment was conducted under a vertical nutrient film technique (NFT) at the Agricultural Research Council – Vegetable, industrial and Medicinal Plants (ARC-VIMP), located in Roodeplaat, South of Pretoria, South Africa (25°59' S; 28°35' E). The experiment was conducted in different environmental conditions (non-temperature-controlled plastic tunnel and a 60% white shade net structure were used as the growing conditions). The system design consisted of a nutrient film technique (NFT) hydroponic system, where polyvinyl chloride (PVC) pipes, steel support, 25 mm pipes and drip spaghetti tubes are used. The operation is through recirculation of a nutrient enriched solution. An A-frame structure was made of steel frame, PVC pipes (including manifold and drainpipes), PVC pipe caps, irrigation pipes and couplings, electrical connection and net cups (diameter = 50 mm; depth = 54 mm). The trial was conducted during the 2020-2021 growing season.

8.2.2 Determination of economic parameters

8.2.2.1 Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis (CBA) is a widely used method for systematically assessing the advantages and disadvantages of a particular intervention and its alternatives (Croft et al., 2017). It will be used here, as a cohesive method to evaluate the costs and benefits of hydroponic production system. This study will then follow the Lazo and Gonzabay (2020) approach and use the following metrics to conduct the cost and benefit analysis utilizing available secondary data to estimate the NPV, IRR and BCR and this study shall follow Mdlulwa et al. (2018) steps in coming up with the discount rate. Authors stated that, one of the best proxies for the discount rate is the average yield on bonds issued by the government employer. The average South African treasury bond yield over the 1993-2018 period is 10.76 per cent (FRED, 2018), hence for analysis, their study adopted a 10 per cent discount rate. Since farm-specific growth rates are not constant over time, growth domestic product (GDP) rate was used.

8.2.2.2 Determination of the Net present Value

The following economic indicators: NPV, IRR and BCR will be calculated. NPV is the present value of an investment's revenue stream (NPV). It's the value of the incremental net benefit or incremental cash flow stream in the present (Lazo and Gonzabay, 2020). The formula is used to compute it mathematically.

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \qquad \text{Equation 4}$$

Bt= Benefits of hydroponic crop production

Ct=Costs of hydroponic crop production

t=Period

n= Number of years

i= Interest (discount) rate.

When NPV is greater than 0 the project is accepted if it is less than 1 the project is rejected.

8.2.2.3 Internal Rate of Return

The IRR discounts all the cash-back in addition to that giving zero NPV during the investment life of a project (Croft et al., 2017):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} \qquad \text{Equation 5}$$

8.2.2.3 Benefit Cost Ratio

The BCR is computed theoretically as the present value of the benefit stream divided by the present value of the cost stream:

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}} \qquad \text{Equation 6}$$

When the cost and benefit streams are discounted at the opportunity cost of capital, the official selection criterion for the BCR measure of project worth is to approve all independent projects with a BCR of 1 or higher. The BCR can be used to determine how much the cost of hydroponics production can climb before they become unprofitable (Lazo and Gonzabay, 2020).

8.3 Results and discussion

8.3.1 Costs of lettuce production under shadenet

Table 8.1: Costs of lettuce production under a shadenet.

Item	Specifications	Quantity	Unit cost (R)	Total Cost (R)
Initial capital investment				193 014,50
Fixed costs:				
Construction of house structure	60% white shade net	400 m^2 (material needed for a 300 m^2 structure)	46 per m^2	9200
Complete NFT vertical A-frame system	6 m long, 2.1 m high, with 14 growing PVC pipes (7 per side), net cup holes spaced at 10 cm, each hole with one cup, 260-L water tank, and two sets can fit on a 300 m^2 structure	12 6 m long complete A-frame systems	12 000	144 000
	Treated wood poles 19 mm/25 mm-3 m long			450
				153 650
Variable costs:				
Water (L)	Lettuce using intermittent water flow (fertigation for 15 minutes every two hours), irrigation using municipal water	0.06 L per plant per day – total amount for one full harvest cycle (six weeks) and full shade net structure which accommodates a total of 10 000 plants = 27 000 L	10.5 per KL	283.5 x 5 =
Electricity	Intermittent water flow patterns (15 min every two hours, no water supply at night-time), gives a total of 180 minutes (3 hours) per day.	101.25 kwh for the entire 45-day harvesting cycle and full structure planting	1.85 per KWH	187.3 x 5
				936,5
Seedlings	Lettuce – Major Iceberg (SA) 22	10 000 seedlings per 300 m^2 structure	420 per 1000 seedlings	4 200 x 5 =21 000
Insect sticky traps	Insect catcher	30	115	115 x 5 =575
Labour	Very low labour requirements for recirculating systems	One person for two hours a day, every day for the duration of the cycle	23.19 per hour	2 087.1 x 5 = 10 435,5
				Per person
Sundry costs				1 000 x 5=50
Total				39 364,50

8.3.2 Costs of lettuce production under plastic tunnel

Table 8.2: Costs of lettuce production under a plastic tunnel.

Item	**Specifications**	**Quantity**	**Unit cost (R)**	**Total Cost (R)**
Initial capital investment				**271 687,40**
Fixed costs:				
Construction of house structure	Plastic Tunnel	400 m^2 (material needed for a 300 m^2 structure)	200 per m^2	80 000
	Treated wood poles 19 mm/25 mm-3 m long	15 x 3 m pole	30 Per pole	450
Complete NFT vertical A-frame system	6 m long, 2.1 m high, with 14 PVC pipes (7 per side), net cup holes, each hole with one cup, 260-L water tank, and two sets can fit on a 300 m^2 structure	12 6 m long complete A-frame systems	12 000	144 000
Total				**224 450**
Variable costs:				
Water (L)	Lettuce using intermittent water flow (fertigation for 15 minutes every two hours), irrigation using municipal water	0.06 L per plant per day – total amount for one full harvest cycle (4 weeks).	10.5 per KL	283.5 x 6 =1701
Electricity	Intermittent water flow patterns (15 min every two hours, no water supply at nighttime), gives a total of 180 minutes per day	101.25 kwh for the entire 45-day harvesting cycle and full structure planting	1.85 per KWH	187.3 x6= 1123,8
Seedlings	Lettuce – Major Iceberg (SA) 22	10 000 seedlings per 300 m^2 structure	420 per 1000 seedlings	4 200 x 6= 25200
Insect sticky traps	Guardi`n`aid insect catcher	30	115	115 x 6= 690
Labour	Very low labour requirements for recirculating systems	One person for two hours a day, every	23.19 per hour	2 087.1 x 6 =12522,60

Item	Specifications	Quantity	Unit cost (R)	Total Cost (R)
		day for the duration of the cycle		Per person per month
Sundry costs				1 000 x 6 =6000
Total				**47 237,40**

8.3.3 Economic feasibility comparison for lettuce production under shadenet vs plastic tunnel

Table 8.3: Economic feasibility comparison for lettuce production under Shadenet vs Plastic Tunnel.

Hydroponic structure	Profit (R)	Net Present Value (R)	Payback Period (Years)	Internal rate of return (%)	Benefit-Cost ratio (R)
PLASTIC TUNNEL	72 762,60	64 602,98	3	14	1,10
SHADENET	35 635,50	121422.65	2	30	1,63

8.4 Conclusions and recommendations

- Lettuce production under shadenet proved to be more viable than that under plastic tunnel;
- This is because shadenet production has a higher NPV than the plastic tunnel;
- Also, the initial investment will be recovered in a shorter period of 2 years;
- Further, the project's investment will yield 30% annual rate of return over its life;
- Moreover, a shadenet can be more durable than a plastic tunnel, which would lead to a more profitable production in the long term.

For more accurate analysis of costs and benefits of production, the economic feasibility analysis should take into account not only direct but also and indirect costs of production, including depreciation and amortization costs.

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CHAPTER 9: GENERAL CONCLUSIONS AND RECOMMENDATIONS

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9.1 General conclusions

Active recovery or recirculating hydroponic systems are gaining increasing popularity, not only in South Africa but also in other parts of the world. The most commonly implemented systems are the horizontal nutrient film technique (NFT), the ebb-and-flow and the gravel film technique (GFT). These systems often operate under shade nets, which is the most popular type of structure used for hydroponics production particularly in South Africa, followed by non-temperature controlled tunnels. Research on vertical NFT systems under both, controlled and non-controlled environmental conditions is still very limited, despite the noticeable potential of these systems for increased land, water and nutrient use efficiencies in crop production.

Recirculating hydroponics is a sustainable and efficient method of agriculture that can be used to grow crops with minimal use of water and other resources. It can be particularly useful in countries with water scarcity, such as South Africa. This project has shown the great potential of this technology as a climate smart-agriculture strategy. A clear example of this beneficial effect of recirculating hydroponics systems was the ability to shift tomato production start of the season to late summer and extended the season to early winter, while producing consistent yields.

This project generated for the first time thresholds of electrical conductivity (EC) levels of the grave film recirculating hydroponic system. The generation of such knowledge is critical in active recovery systems, since the frequency of refill solution is determined by the ratio of solution volume to plant growth rate. In addition, the tolerance of nutrient imbalance in the solution may be a crop-specific factor, as some crops can have higher ability than other crops, to store the nutrients that were rapidly absorbed from the solution in roots, stems or leaves, and remobilize them as needed.

Prior to implementation of this project, there was limited information in terms of crop water and nutrients used in hydroponics. This project was among the few contributing to existing information on this matter. Such information is critical for hydroponic systems, as these systems operate on the basis of a recirculation of the nutrient solution, making them very likely to be water- and nutrient-use efficient. The generation of such knowledge will help promote the utilization of these systems in crop production and to influence policy decision-makers towards a positive perception and attitude on the use of recirculating hydroponic systems for crop production. This is of utmost importance in a water-scarce country like South Africa, where there is limited water allocations to growers, in spite of the growing demand for food production.

The need for hydroponics in urban environments was clearly articulated using rooftop farming as an example. Similarly, the potential for hydroponics to draw young people to agriculture was also identified. Hydroponics can also be used to increase the amount of households involved in agricultural activities within Gauteng Province. Hydroponics is a sustainable way of producing food within urban environments and it is a farming technic that inherently nested within the Water Energy Food nexus. It has relatively low water and energy requirements.
All three technologies developed/ tested throughout the implementation of this project were successfully validated under farmers' condition. Major drawbacks were identified and recommendations made to address them. Loadshedding was among the biggest challenges for hydroponic farmers. This was coupled to limited market strategies and relatively low skills to operate, manage and maintain hydroponic systems.

9.2 General recommendations for future work

There is a need to conduct further research on the following aspects of recirculating hydroponic systems:

- Optimum cultivation practices for a range of potential crops such as lettuce, basil and strawberry grown under vertical recirculating systems;
- Optimization of hydroponic systems operational parameters, including water flow rates and concentrations of the nutrient solution under different environmental conditions, hydroponic systems and structures;
- Viability of renewable energy utilization in hydroponics, such as solar and wind – derived energy systems.

To fasten the adoption and mass utilisation of recirculating hydroponic systems, several policy recommendations need to be considered. Primarily, the government could increase funding and offer other financial incentives to resource-poor and emerging commercial farmers that are interested in adopting recirculating hydroponics. This would help to offset the initial costs of setting up a hydroponic system and encourage more farmers to use this technology. The government could also increase partnerships with research institutes and the private sector to develop training and mentoring programs to teach farmers how to use recirculating hydroponics effectively and efficiently. This would help to ensure that farmers have the knowledge and skills they need to succeed with this technology. Furthermore, the government could develop regulations to ensure that recirculating hydroponics systems are safe, efficient, and environmentally sustainable. This would help to protect the health of consumers and the environment and promote the long-term viability of this technology

10. APPENDICES

10.1 Student capacity building

Project number C2019/2020-00229, titled "Technology exchange and training of active, recovery hydroponic systems for vegetable production in the Gauteng Province, South Africa" involved one PhD and one MSc students. The student's personal information is indicated in Table 67.

Table 9.1: Personal details of the post-graduate students contributing to capacity building under project C2019/2020-00229.

No	Name	Type of beneficiary	Institution/ company	Date of first-time registration	Development topic
1	Makgoka Given Moremi	PhD student	University of Pretoria	01-May-2020	Improving land use, water and nutrient reuse efficiencies in a vertical NFT hydroponic system for cultivation of high-value vegetable and herb crops
2	Lucy Nani Masilela	MSc student	Tshwane University of Technology	01-May-2022	Improving post-harvest quality of leafy crops grown under a vertical recirculating hydroponic system

Mr Makgoka Moremi' PhD degree progressed as follows during the duration of project implementation:

- completed two seminars at University of Pretoria. He is currently preparing two scientific manuscripts for submission to peer-reviewed international journals.

- presented his research finding at the Combined Congress conference, in January 2022 and 2023.

- contributed to three book chapters submitted for publication in Springer Nature, Elsevier and DALRRD – BRICS Event.

- submitted one abstract to ISHS international symposium on disinfection of soilless substrates. The abstract was approved for oral presentation. A detailed scientific manuscript was compiled and submitted for publication in Acta.

- compiled two scientific manuscripts for publication in Scientia Horticulturae and Agronomy journals.

Ms Lucy Masilela has made substantial progress to date. She completed postharvest trials on lettuce, sweet basil and parsley. She is currently consolidating her dissertation (all chapters have already been written in the form of scientific manuscripts). Ms Masilela made one poster presentation at the Combined Congress 2023 and one oral presentation at the South African Association of Botanists in 2023.

10.2 Knowledge creation during the project implementation period

10.2.1 Knew knowledge created

- The unique hydroponics planting system designed and built by AB Farms was successfully tested. Its effectiveness in terms of water and electricity utilization, farming density and overall ability to solve food security in the context of WEF nexus were demonstrated;

- A vertical nutrient film hydroponic system was improved through on-station and on-farm trials conducted by the Agricultural Research Council to better suit farmers environmental conditions, with the aim of increasing farmers productivity, market access and profitability. This improved system is water, energy, space and labour efficient;

- Through the implementation of this project, novel crop production management practices were generated by the Agricultural Research Council Team. This project generated first-time insight on the water usage, water productivity and nutritional water productivity of vegetable crops produced in recirculating hydroponic systems;

- In addition, the generated knowledge contributes to the limited information available on post-harvest technologies for preservation of fresh produce and quantification of costs and benefits obtained through the implementation of the various technologies introduced to farmers.

10.2.2 Gaps expected to be filled by new knowledge

- All hydroponic systems require water to be flowing through them continuously, this requires uninterrupted water and electricity supply which is often not possible in South Africa and other African countries. The hydroponics planter tested in this project bridges this gap by allowing periodic irrigation;

- The standard operatizing procedures being created will help future end users to use the system and obtain good results. The system also opens the possibility of low cost solar systems being used to operate vertical hydroponic systems entirely off grid. This is possible because of the low energy requirements of periodic water flow compared to continuous water flow. Solar energy utilization is also being studied;

- Hydroponic farmers have limited awareness of the water and fertilizer usage in hydroponic systems. This project will narrow these gaps in research.

10.2.3 Innovation in the new products developed

- The hydroponic systems tested in this project enable the efficient application of urban farming, they can increase the amount of households involved in agricultural activities in urban, townships and peri-urban environments thus boosting food security on a household level whilst populations increase. The systems allow increased planting densities per m^2 which is helpful to emerging farmers who have limited access to land.
- The tested technologies will be useful to farmers, policy decision-makers, students and entrepreneurs.

10.2.4 Envisaged application of technologies tested

- The process of early adaptation for the hydroponics planter technology has started. A customer validation exercise was conducted, which included a survey with potential consumers to determine the correct product-market fit. In addition, household sized systems were sold to two clients and a medium sized system was set up in a school in KZN this particular system will be used for educational purposes and the produce will be used within their feeding scheme program.
- The Agricultural Research Council has built a solid, trustworthy relationship with farmers, post-graduate students and young entrepreneurs. It is through this long-lasting relationship that ARC researchers reached an understanding of what the local industry requires to solve major challenges nationwide, including food insecurity, water scarcity, land conflict issues, limited availability of arable land, very confined spaces available for food production in urban areas, job losses exacerbated by the occurrence of COVID-19 pandemic while, on the other hand, people have limited land available to produce own food. In addition, water scarcity is a major issue in the country. This project addresses this problem, by introducing to farmers water-efficient recirculating

systems. Moreover, the developed systems operate under protected environmental conditions, which contributes to a mitigation of the adverse effects of climate change.

10.3 Knowledge generation and dissemination

10.3.1 Popular articles published in magazines

- N Araya, M Sithole, A Laas, M Truter, B Murovhi, S Venter and I du Plooy, 2023. Hydroponics in the context of water-energy-food nexus: a world's eye-catching matter. ARC – Vegetable, Industrial and Medicinal Plants News Letter No 10, published on 30 January 2023.
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10.3.2 Pamphlets produced

- Araya N, 2022. A guide for self-establishment of a bag system “grow your own vegies at home”. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants.
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- Masilela L, 2023. A guide on how to package and store the coriander herb “Quality is everyone's duty”. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants.
- Araya N, 2022. How to care for a bag hydroponic system. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants.
- Araya N, 2023. Design and set-up of a vertical NFT hydroponic system for production of leafy vegetables and herbs. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants.
- Maleka M and Pule T , Hydroponic Pamphlets (Vertical hydroponics explained)

10.3.3 Conference presentations

- Moremi MG, Araya NA and Steyn JM, 2023. Growth, yield, and water use efficiency response of lettuce as affected by water flow, plant spacing, and environmental conditions in a vertical nft hydroponic system. Combined Congress 2023, University of Pretoria, Poster Presentation.
- Masilela LN, Mampholo BM, Soundy P and Araya NA, 2023. Assessing pre- and post-harvest responses of coriander grown under a vertical nft system ,Combined Congress 2023, University of Pretoria, Poster Presentation.
- Maleka M and Pule T, 85th IMESA conference, 2-4 November 2022.
- Maleka M and Pule T, 2020 Dubai Expo, 23 March 2022.
- Maleka M and Pule T, WISA Workshop – Research & innovation stemming the Tide: Reflecting on 6 years of Water RDI Roadmap Implementation.
- Maleka M and Pule T, WISA & SASTEP Biennial conference & exhibition, 28 September 2022.
- Maleka M and Pule T, Giyani Local Scale Climate Resilience Program Expo, 28 February 2023.
- Maleka M and Pule T , Giyani SASTEP & WRC: Showcasing of Aquonic Sanitation and Hydroponic system in Giyani 28-29 September 2023.

10.3.4 Radio/Podcasts/Interviews

- AB Farms' Mogale Maleka speaks to Newzroom Afrika about hydroponics. https://www.youtube.com/watch?v=FcyMRzwO1Il&list=LL&index=26
- Vuk Talks 'Amplify, Build and Connect' with Dimpho Mogale and Kwena Molekoa – Episode 2. https://www.youtube.com/watch?v=89ebGqlImDU&list=LL&index=7&t=826s

10.3.5 Training and Farmers' Days Events

- ARC Team in partnership with Farmers and Stakeholders, February 2023. Johannesburg, Zuurbekom, Mme Mbatha and Mme Zodwa Framers' site.
- ARC Team in partnership with Farmers and Stakeholders, March 2023. Johannesburg, AgriParks, Rooiwal Framers' site.
- ARC Team in partnership with Farmers and Water Research Commission, August 2022. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants. Water-Energy-Food Nexus Winter School.
- ARC Team in partnership with Farmers and Water Research Commission, August 2023. Agricultural Research Council – Vegetable, Industrial and Medicinal Plants. Water-Energy-Food Nexus Winter School.
- AB Farms trained several clients in KZN, Sandton, Botswana, Klercksdorp and Giyani.

10.3.6 Book chapters published

- Nadia Alcina Araya, Makgoka Given Moremi, Salmina Mokgehle, Motiki M. Mofokeng, Mantwampe Johleen Malaka, Manaka Makgato, Hintsa Tesfamicael Araya and Beverly Mampholo, 2023. Sustainable soilless recirculating hydroponics for productive use of marginal lands: a south african context. Accepted for publication in Springer Nature.

- Moremi MG, Sithole MA, Malatjie E, Hlophe-Ginindza SN, Nhamo L, Mpandeli S, Truter M, du Plooy CP and Araya NA , 2023. Recirculating hydroponics as a climate-smart crop production technology: a case study of the gravel film technique. In: Climate-smart agriculture: evidence-based case studies in South Africa, ISBN 978-0-621-51347-9.

10.3.7 Scientific publications in progress

- Makgoka Moremi, J. Martin Steyn, Christian du Plooy and Nadia Araya, 2024. Effects of water flow rate and nutrient solution concentrations on sweet basil growth, yieldbiomass production and water use efficiency in a closed hydroponics system. To be submitted to Agronomy MDPI.
- Makgoka Moremi, J. Martin Steyn, Christian du Plooy and Nadia Araya, 2024. Nutritional water productivity of sweet basil as affected by nutrient solutions concentrations and water flow rates in a closed hydroponics system . To be submitted to Scientia Horticulturae.
- Rebecca Mahlangu, Beverly Mampholo, Neo Nyakane, Hlabana Seepe, Makgoka Moremi, Hintsa Araya, Ian du Plooy, Stephen Amo, Abenet Belete and Nadia Araya, 2024. Post-harvest quality and economic feasibility of leaf lettuce produced under a vertical nutrient film technique in response to different pre-harvest spacing and packaging types. To be submitted to Postharvest Technology.
- Mogale Maleka, Tumelo Pule, Makgoka Moremi, Mduduzi Sithole, Arone Baloi, Abenet Belete, Samkelisiwe Hlophe-Ginindza, Ian du Plooy and Nadia Araya, 2024. Water use, yield, and profitability of green and red lettuce varieties grown under two different vertical circulating hydroponic systems in emerging commercial farms: a case study of South Africa. Water SA.

10.3.8 Educational video produced

- ARC / WRC Production, 2024. Recirculating hydroponics: a climate-smart crop production system. First draft produced by PlaasMedia, expected to be disseminated by December 2024.